Clouds and Filaments: The Initial Conditions of Star Formation

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Infrared dark clouds (IRDCs) are seen in absorption against the mid-infrared background and are thought to represent likely sites of future massive star formation. We investigate these IRDCs to probe the conditions present when star formation begins. The Spitzer dark cloud (SDC) catalogue contains \( \sim 11,000 \) IRDCs. We extend this catalogue to include the inner 20° of the Galactic plane, adding 4334 SDCs to the catalogue. Some of the objects in the catalogue are artefacts - ‘dips’ in the mid-infrared emission rather than regions where the emission is absorbed. With the advent of data from the Herschel satellite, we are able to construct column density maps of the objects in the SDC catalogue to identify which SDCs are true IRDCs and which are artefacts. We compare the properties of the IRDCs in the Galactic centre and in star forming regions with those in more quiescent regions. We find that the IRDCs towards star forming regions and the Galactic centre tend to have a higher column density and a slightly higher temperature, implying that the conditions within IRDCs are dependent on the environment in which they are found.

Star formation has long been associated with filaments. Filaments containing long strings of IRDCs have been observed in the Galactic plane. We apply a minimum spanning tree (MST) algorithm to the SDC catalogue to identify 88 filamentary candidates, 22 of which appear to be isolated, linear filaments similar to the Nessie nebula. Filaments tend to fragment into clumps regularly spaced along the length of the filaments. We compare theoretical predictions of this fragmentation with the clumps observed in the 22 linear filaments identified by the MST algorithm and find our results are consistent with those predicted by the sausage instability for filaments dominated by thermal pressure.
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1

Introduction

1.1 Massive Stars

Massive stars (M > 8M$_\odot$) play an important role in the evolution of galaxies. They are the main source of heavy elements, which are responsible for cooling the interstellar medium (ISM), and the main source of UV radiation, which is responsible for heating the ISM. Stellar winds and supernovae drive turbulence in the ISM and may trigger star formation in nearby regions (Zinnecker & Yorke 2007). There is some evidence that massive stars in starburst galaxies can drive Galactic winds (Kennicutt 2005) and their UV radiation affects the formation of lower mass stars and planets in their vicinity (Bally et al. 2005).

However there are several factors which make understanding the formation of massive stars difficult. Massive stars often form in clusters along with lower mass stars, yet they must form much more rapidly. The typical lifetime of a high mass star is 10$^6$ years; implying that a high mass star must form on timescales of 10$^5$ years. By contrast a low mass star may take 10$^7$ years to reach the main sequence and have a main sequence lifetime of $\sim$10$^{10}$ years. Massive protostars must therefore have much higher accretion rates than lower mass protostars. Massive stars have a short Kelvin-
Helmholtz timescale. The Kelvin-Helmholtz time is the time it takes for a star to radiate away all its gravitational potential energy as it collapses and is therefore given by $t_{KH} = \frac{G M^2}{L R}$, where $L$ is the luminosity of the protostar and $G M^2/R$ is the gravitational potential energy of the collapsing protostar. A typical value of $t_{KH}$ is $10^5$ yr for a $30 M_\odot$ protostar, indicating that massive protostars reach the main sequence in around $10^5$ yr. Thus massive stars must accrete sufficient mass in less than $10^5$ yr, giving accretion rates of around $10^{-4} M_\odot$ yr$^{-1}$ (c.f. $10^{-7}$ to $10^{-8} M_\odot$ yr$^{-1}$ for low mass stars) \cite{McKee&Tan2002}.

The short Kelvin-Helmholtz timescale results from the high luminosity of high mass protostars. This high luminosity causes the radiation pressure to be sufficiently high to halt accretion onto the protostar. As a result, standard models of star formation, such as the core-collapse model, provide accretion rates that are too low to explain massive star formation. More recent models have been developed to provide a mechanism by which accretion can continue despite the radiation pressure from the core. One such model suggests that rapid accretion onto massive protostars can be achieved with the presence of a ‘bloated’ envelope with a contracting inner core. This allows temperatures to remain less than $10^4$ K and the envelope to be transparent to radiation, reducing the radiation pressure and therefore allowing the rate of accretion to increase \cite{Hosokawaetal2013}. Nevertheless the processes behind such high accretion rates remain unclear.

Feedback in the form of stellar winds and UV radiation from young massive stars destroy the environment in which they formed, yet massive stars are observed in stellar clusters with stars of all masses. As low mass stars form more slowly than high mass stars, star formation must continue after the more massive stars have formed, despite the disruption to the surrounding medium. The influence of this feedback on low mass protostars and young stellar clusters is not yet understood.
The formation of massive stars must therefore differ from the formation of low mass stars. Several models have been suggested to explain massive star formation, including by accretion via a disc (Shu et al. 1987), competitive accretion in clusters (Zinnecker 1982; Bonnell et al. 1997) and through stellar mergers (Bonnell et al. 1998; Clarke & Bonnell 2008). It is possible that these models are all important in different environments.

1.2 Possible Modes for Massive Star Formation

1.2.1 Accretion

Massive stars cannot form in the same way as lower mass stars, i.e. an initial protostar is formed from a core and the protostar gains mass by accretion from the mass reservoir provided by the core. The radiation and mass outflow from the central object could disrupt this accretion, preventing the star from gaining mass. However if accretion occurs via a disc with outflows at the poles this would cease to be a problem (see Figure 1.1). One such disc has been observed around a high mass protostellar object by Kraus et al. (2010) and polar jets have been observed by de Wit et al. (2009); Carrasco-González et al. (2012).

Numerical simulations by Krumholz et al. (2009) show that disc accretion and polar outflows can provide a mechanism to form massive stars (see Figure 1.2). Krumholz et al. described how two stars of mass 41.5M$_\odot$ and 29.2M$_\odot$ were formed in a binary system from a gas cloud with a mass of 100M$_\odot$ in a three-dimensional simulation on a time-scale of $5 \times 10^5$ years; the formation time of massive stars. Initially a single protostar condensed out of the gas and accreted matter through an axisymmetric disc forming a central object with a mass 11M$_\odot$. After this point the disc became a two armed spiral as gravitational instabilities developed in the disc and accretion continued via the spiral. At 17M$_\odot$ radiation pressure exceeded the gravitational potential and
Figure 1.1: Schematic showing the accretion of mass onto a central object by disc accretion with cavities at the poles created by outflows. These outflows are caused by radiation and stellar winds from the central object (Zinnecker & Yorke 2007)

gas outflows formed at the poles, creating radiation bubbles, however the accretion rate was unaffected. Fragmentation then occurred in the disc and smaller objects were formed in the disc. These objects eventually coalesced leaving two remaining objects, the original object and a smaller binary star.

Although such simulations provide a mechanism by which massive stars can form despite the radiation pressure created by the central object it is not yet a complete picture. The cores from which massive stars form contain many Jeans masses and yet do not fragment to form several low mass stars rather than one or two high mass stars (Dobbs et al. 2005). There must be something preventing the core from fragmenting further. Strong magnetic fields in one star-forming clump have been observed by Girart et al. (2009) and this may suppress fragmentation (Commerçon et al. 2011) Myers et al. 2013). Radiative feedback from protostars in the clump may also be important in preventing fragmentation (Krumholz 2006). Simulations have not yet incorporated
1.2.2 Competitive Accretion

Competitive accretion explains how some stars may have very high accretion rates by considering forming stars, not in isolation, but as part of a cluster. In the centre of
clumps (the progenitors of stellar clusters) the gravitational potential will be greater, resulting in a greater density of gas due to the infall of mass towards the centre of the clump. This effect will be enhanced once a few stars have condensed from denser regions of gas (Zinnecker & Yorke 2007).

Bonnell et al. (1997) describe how initial proto-stellar cores collapse, creating an under-density of gas in the surrounding cloud. Gas from further away, that is initially unbound to any of these cores, then moves in to this underdense region. However the incoming gas now feels an additional potential due to the clump as a whole and so will preferentially move to the centre of the clump. Hence those stars at the centre of the clump and those stars which collapse out of the cloud first will accrete mass preferentially over the others. This suggests the most massive stars should be found near the centre of star clusters, which seems to match observations (Hillenbrand et al. 1995).

Numerical simulations such as those by Bonnell et al. (2003) suggest that lower mass stars are formed first by fragmentation of the clump, then those nearest the centre of the clump go on to gain more mass due to the potential of the clump. Further simulations by Bonnell et al. (2007) have found Initial Mass Functions (IMF), the mass distribution of stars formed in a cluster, that match observations.

However such simulations have come under criticism, for example Krumholz et al. (2005) suggests that competitive accretion does not work in a turbulent medium. Turbulence in the molecular clouds from which stars form can be high, with linewidths of 10kms$^{-1}$ observed (Ossenkopf & Mac Low 2002). In addition magnetic fields have yet to be included in simulations and may act to reduce the rate of accretion (Cunningham et al. 2012). It is also clear that massive stars do indeed form in isolation, away from clusters (Bressert et al. 2012), implying that competitive accretion alone is insufficient to explain how massive stars form.
1.2: POSSIBLE MODES FOR MASSIVE STAR FORMATION

1.2.3 Stellar Mergers

A final way of forming massive stars is through stellar mergers, where two or more stars interact in such a way that they merge to form a much larger star. Stellar mergers do not require the high accretion rates (up to $10^{-3} \text{M}_\odot \text{yr}^{-1}$) required to form a star through accretion (Beuther et al. 2007). However in order to form massive stars in this way during the star formation phase of a cluster, collisions must take place before the most massive star evolves off the main sequence i.e. the collision time must be less than $\sim 3 \text{Myr}$ (Zinnecker & Yorke 2007).

The average time it takes for a star to undergo a collision, $t_{\text{coll}}$, is given by Equation 1.1 (Binney & Tremaine 1987). Here $R_{\text{min}}$ is the minimum distance required for an interaction between two stars of mass $M_\ast$ in a cluster of stellar density $n_{\text{star}}$ and root mean square velocity $v_{\text{rms}}$.

$$t_{\text{coll}} = 7 \times 10^7 \left[ \frac{n_{\text{star}}}{10 \times 6 \text{pc}^{-3}} \right]^{-1} \left[ \frac{M_\ast}{10 \text{M}_\odot} \right]^{-1} \left[ \frac{R_{\text{min}}}{R_\odot} \right]^{-1} \left[ \frac{v_{\text{rms}}}{10 \text{kms}^{-1}} \right] \text{yr} \quad (1.1)$$

Even with large estimates for $v_{\text{rms}}$ and the cross section for stellar interactions increased to include discs and binary systems, the minimum stellar density for stellar conditions to be important is $10^6 \text{pc}^{-3}$ (Bonnell & Bate 2005). This is higher than observed for young stellar clusters; McCaughrean & Stauffer (1994) observed stellar densities of $\sim 5 \times 10^4 \text{pc}^{-3}$ in the Trapezium. However stellar mergers may be possible in the densest young star clusters. The requirement of such a high stellar density indicates that whilst stellar mergers may occur, they are not the dominant mode of star formation.

1.2.4 Triggered Star Formation

The initial stages of star formation may be influenced by external triggers such as a supernova or stellar winds. Such events blow away surrounding gas and, in the case of supernovae, gas from the star also expands into the surrounding interstellar medium.
This creates a shock wave that moves out from the initial event. If this shock wave interacts with a GMC the shock wave can compress any overdense regions already present or the swept up material can collide with a nearby cloud and so cause overdense regions to form, triggering a new phase of star formation [Elmegreen 1998]. Hence as one cluster of stars forms, the material blown away in outflows by the forming star can trigger star formation in a nearby region of a GMC. This creates an age sequence of stellar clusters in the same vicinity.

The triggering of star formation due to an expanding HI region has been observed in the Large Magellanic Cloud by [Dopita et al. 1985]. A ring of HII regions, indicating star formation, was observed surrounding a region empty of HII, suggesting an event in the centre of the ring had created a shock wave that had moved outwards, triggering star formation along the way. More recently, [Thompson et al. 2012] found that there is an overdensity of young stellar objects (YSOs) associated with bubbles of expanding material identified by [Churchwell et al. 2006]. Thompson et al. found that these YSOs tend to be concentrated around the rim of the bubble where the material is at its densest. Similar results have been found by e.g. [Choudhury et al. 2010]; [Brand et al. 2011]; [Dewangan et al. 2012].

While triggering mechanisms may start or enhance star formation in some circumstances, they may also halt or delay star formation in others. [Dale et al. 2007] carried out numerical simulations in which ionising photons were included as a triggering mechanism and compared them with simulations without triggering mechanisms. They found that almost twice as many stars were formed and the overall star formation efficiency was increased by a third, indicating that star formation may be enhanced by ionising photons. However it remains unclear how great an impact triggering mechanisms have on the rate or efficiency of star formation in a GMC or how many stars would be formed anyway, without such external mechanisms.
1.3 Initial Conditions of Star Formation

To understand how massive stars form, we must look at the initial conditions present when star formation begins.

1.3.1 Molecular Clouds

Observations show that star formation occurs in molecular clouds; clouds of gas dominated by molecular hydrogen containing simple molecules such as CO. Indeed star formation is closely linked with the presence of H₂. Observations of galaxies by Leroy et al. (2008) and Bigiel et al. (2008) show that the rate of star formation is correlated with the surface density of H₂, but not with the surface density of atomic hydrogen. Molecules, particularly CO, provide a mechanism to cool the gas, reducing the thermal support of the cloud and allowing gravitational collapse to occur (Neufeld et al. 1995). However, simulations by Glover & Clark (2012) indicate that star formation is not dependent on the presence of molecular hydrogen or CO, but that the same conditions are required for both molecules and stars to form. Glover & Clark suggest that both processes require shielding from interstellar radiation, preventing molecules from being dissociated and preventing the gas from being heated. This allows the temperature to decrease and gravitational collapse of the clouds to occur. Such shielding can only occur if the density of the gas is sufficient to prevent photons penetrating into the cloud.

Several mechanisms have been suggested for the formation of such dense clouds. Simulations by Vázquez-Semadeni et al. (2011) show that molecular clouds can form from colliding gas flows. Such flows may be due to stellar winds, supernovae or turbulence in the interstellar medium. When the streams converge, the local density is increased, allowing shielding to occur and the gas to become molecular. Ntormousi et al. (2011) show how the collision of two expanding shells of gas can lead to the formation of molecular clouds in the region where the two bubbles overlap. Such simulations produce molecular clouds that have a mass of up to \( \sim 10^4 \text{M}_\odot \), however as molecular clouds
have been observed with masses of the order $10^7 M_\odot$ this mechanism is only likely to be important in the formation of smaller clouds.

Simulations by Dobbs et al. (2012) suggest that such smaller clouds can be amalgamated into larger Giant Molecular Clouds (GMCs) of masses $>10^6 M_\odot$. Collisions between clouds are unlikely in the ISM except in the spiral arms, where clouds will be slowed due to the gravitational potential of the spiral arms. This leads to ‘orbit-crowding’ where clouds are much more likely to collide to give larger clouds which may become gravitationally bound (Moore et al. 2012). In addition, the passage of the spiral arms through the ISM may itself form molecular clouds Bonnell et al. (2006); the shock at the leading edge of the spiral arms causes the density of the gas to increase and the denser regions may become dense enough to become gravitationally unstable and hence collapse to form stars.

The star formation efficiency of molecular clouds is low at $\sim 1 M_\odot$/yr in the Milky Way, with only $\sim 1\%$ of the mass in molecular clouds converted to stars (Krumholz et al. 2012). This low efficiency implies that molecular clouds are supported against collapse. This support was thought to be provided by magnetic fields, however observations by Crutcher (2012) show that the magnetic fields in molecular clouds are not strong enough to support the clouds. Turbulence can provide a support against gravitational collapse; molecular clouds have linewidths of up to $10 \text{ km s}^{-1}$ which is sufficient to suppress star formation (Ossenkopf & Mac Low 2002). Finally molecular clouds may be disrupted by stellar winds from newly formed protostars, halting star formation and reducing the star formation efficiency. In reality, some or all of these may be responsible for keeping the rate of star formation in molecular clouds low.

Whilst turbulence (random flows of gas on all scales) within a cloud can create regions of overdensity from which gravitational collapse can form stars, it can also disrupt these dense regions before star formation can begin (Mac Low & Klessen 2004).
Hence star formation is suppressed if the total kinetic energy due to turbulent motions is greater than the total gravitational potential energy of the cloud (Padoan & Nordlund 2011). As such, supersonic turbulence results in inefficient, isolated star formation with GMCs and hence a low star formation efficiency. Numerical simulations by Klessen et al. (2000, 2005) show how supersonic turbulence can form cores and numerical simulations by Padoan & Nordlund (2011) have produced star formation efficiencies of between 2 and 10%, similar to those observed. However, turbulence decays in less than a free-fall time (Stone et al. 1998) so turbulence must be driven by e.g. colliding flows, expanding shells or shock waves (Mac Low & Klessen 2004).

1.3.2 Infrared Dark Clouds

The coldest and densest parts of molecular clouds are infrared dark clouds (IRDCs). IRDCs were first observed in 1996 by Perault et al. (1996) using ISOCAM at 15µm as absorption features against the infrared background of the Galactic plane. Perault et al. suggested that they are “good candidates to precursors to star formation sites”. Since then, follow-up observations have shown that these sources are potential mass reservoirs for future generations of massive stars (e.g. Teyssier et al. (2002); Simon et al. (2006); Rathborne et al. (2006); Ragan et al. (2006)). IRDCs are typically very cold, with temperatures as low as 8K observed towards the centre (Peretto et al. 2010). They have high densities of up to $8 \times 10^4 \text{cm}^{-3}$ (Longmore et al. 2011) and often show evidence that they have started to fragment into several regions of high density (Peretto & Fuller 2009).

Whilst it is difficult to confirm that IRDCs are indeed sites of massive star formation as massive protostars are deeply embedded in their nascent clouds and dust extinction makes direct observations difficult, some indicators of massive protostars have been observed in IRDCs. Observations by Carey et al. (1998) have found IRDCs with nearby HII regions and H2O masers, indicating star formation occurred in the
area. They also found one cloud containing an embedded infra red source, likely to be a young stellar object. IRDCs have also been observed to contain class II methanol masers (Ellingsen 2006) and jet-like outflows (Wang et al. 2011), both of which are unique indicators of the formation of massive stars. Other signposts of massive star formation have been observed towards IRDCs, such as UCHII (ultra-compact HII) regions (Liu et al. 2013), which represent regions of ionised hydrogen surrounding massive protostars, and EGOs (extended green objects) which represent emission at 4.5\(\mu m\) due to outflows driven by massive young stellar objects (Yu & Wang 2013).

The darkness of IRDCs in the mid-infrared domain ensures that these sources represent early stages of dense cloud evolution, as they have yet to be heated by embedded protostars. IRDCs and the cores they contain thus represent the initial conditions from which massive stars form.

By understanding the initial conditions present when star formation begins, it may be possible to further our understanding of massive star formation. In this thesis we investigate the nature of IRDCs and their distribution throughout the Galactic plane. In Chapter 2 we find IRDCs in the central 20° of the Galactic plane and add them to the Spitzer dark cloud catalogue (Peretto & Fuller 2009) to provide a complete catalogue of objects in the region \(|l| < 65°, |b| < 1°\). In Chapter 3 we investigate the distribution of IRDCs in the Galactic plane and examine the properties of these IRDCs to investigate whether they are affected by their environment. In Chapter 4 we use the catalogue to find filamentary structures containing long strings of IRDCs and in Chapter 5 we characterise the fragmentation of these filaments to investigate the influence of filamentary structures on the first stages of star formation.
Completing and Cleaning the *Spitzer* Dark Cloud Catalogue

The Spitzer Dark Cloud (SDC) catalogue was compiled by Peretto & Fuller (2009) using data at 8µm from the *Spitzer* satellite. The SDC catalogue contains over 11,000 IRDCs seen in absorption against the background emission of the Galactic plane. The SDC catalogue covers the Galactic plane from 10° < |l| < 65°, |b| < 1°; the area covered by the GLIMPSE survey of the Galactic plane Benjamin et al. (2003). With new data at 8µm from GLIMPSEII Churchwell et al. (2009) and GALCEN Stolovy et al. (2005) covering the inner 20° of the Galactic plane, including the Galactic centre, it is now possible to extend the SDC catalogue to include this region. Some of the objects in the SDC catalogue may be artefacts, regions where the 8µm emission drops rather than regions where the 8µm emission is absorbed Wilcock et al. (2012). Observations by Herschel now allow us to observe IRDCs in emission, allowing us to systematically remove artefacts from the catalogue. This will then provide us with a complete catalogue of objects which will enable us to investigate the initial conditions of star formation.
2: COMPLETING AND CLEANING THE SPITZER DARK CLOUD CATALOGUE

2.1 Data

In this chapter we use data from the GLIMPSEII [Churchwell et al. 2009] to extend the SDC catalogue. GLIMPSEII covers the region $|l| < 10^\circ, |b| < 1^\circ$, omitting the Galactic centre ($|l| < 1^\circ$). We use the GALCEN survey [Stolovy et al. 2005], which covers the central region omitted by GLIMPSEII, to provide total coverage of the inner 20° of the Galactic plane. GLIMPSEII and GALCEN use the IRAC [Fazio et al. 2004] camera to take data at 3.6, 4.5, 5.8 and 8µm. We used the GLIMPSEII v1.6 data product release.

Although IRDCs can be seen as absorption features in all the bands up to 24µm and in some cases up to 70µm, differentiating between background fluctuations and IRDCs can be complicated. Naively, we wish to obtain the best possible resolution, making the 3.6µm data the best choice to find IRDCs, however the background emission at 3.6µm is complicated. The background is flatter at 4.5, 5.8 and 8µm, however there are fewer point-like sources at 8µm than at 4.5 and 5.8µm. Hence the 8µm data with a resolution of 2.4″ is used to identify the IRDCs.

With the advent of the Herschel space satellite [Pilbratt et al. 2010], it is now possible to observe IRDCs in emission at 70, 160, 250, 350 and 500µm with a higher resolution than was previously possible (5″, 12″, 18″, 24″ and 36″ respectively), using the two photometry instruments PACS [Poglitsch et al. 2010] and SPIRE [Griffin et al. 2010]. The HiGAL open time key project [Molinari et al. 2010b] has observed the Galactic plane ($|l| < 70^\circ, |b| < 1^\circ$), completely covering the GLIMPSE and GLIMPSE II regions. This allows us to examine the dust emission from all the IRDCs in the SDC catalogue.

The HiGAL data were reduced, as described in [Traficante et al. 2011], using HIPE [Ott 2010] for calibration and deglitching (SPIRE only) and the ROMAGAL map making algorithm. In addition, zero-flux levels for every HiGAL field have been recovered.
by correlating *Herschel* data with Planck and IRAS data (Bernard et al. 2010).

## 2.2 Finding the Opacity

IRDCs absorb the mid infrared radiation that is emitted by PAHs (polycyclic aromatic hydrocarbons) in the Galactic plane, with a small contribution from continuum emission from dust particles. IRDCs are seen as absorption features in the mid-infrared where they have absorbed the emission coming from behind them. The opacity is a measure of how much of the background emission is absorbed by the dust in the IRDCs and is defined by the radiative transfer equation. We can construct maps of the 8\(\mu\)m opacity using the GLIMPSEII tiles and use them to find areas of high opacity which indicate the presence of an IRDC.

### 2.2.1 The Radiative Transfer Equation

The 8\(\mu\)m opacity can be found using a form of the radiative transfer equation (Equation 2.1), where \(I\) is the intensity at the receiver, \(I_{bg}\) is the background emission entering the IRDC and \(\tau_\nu\) is the opacity at frequency \(\nu\).

\[
I = I_{bg}e^{-\tau_\nu} + I_{fore}
\]  

(2.1)

This equation is obtained by considering how the emission coming from behind an IRDC is absorbed as it travels through the cloud. As IRDCs do not emit much at 8\(\mu\)m - they are absorption features - the flux of the 8\(\mu\)m radiation is decreased by a factor of \(e^{-\tau_\nu}\) as it passes through the cloud. The radiation then passes through the interstellar medium (ISM) between the cloud and the receiver. Whilst a small amount of absorption may occur in the ISM, this absorption is negligible (Rieke & Lebofsky 1985), so we assume that there is no further absorption along the line of sight to the IRDC. The contribution from the foreground is therefore assumed to be due to emission
Figure 2.1: Demonstration of the radiative transfer equation. The emission coming from behind the cloud, $I_{bg}$, is absorbed by the cloud, reducing the intensity by a factor $e^{-\tau \nu}$. The radiation leaving the cloud then travels along the line of sight to the receiver, which emits radiation, $I_{fore}$.

only and this emission is simply added to the radiation from the cloud. This process is demonstrated in Figure 2.1. We can therefore rearrange Equation 2.1 to obtain the following expression for the opacity of the IRDC at $8\mu m$.

$$\tau_{8\mu m} = -\ln \left( \frac{1 - I_{fore}}{I_{bg}} \right)$$  \hspace{2cm} (2.2)

Hence the opacity can be calculated from the $8\mu m$ data provided we are able to separate the foreground and background emission.

One way to separate $I_{fore}$ and $I_{bg}$ is to examine the emission of the dust from the IRDCs. The emission from the cloud depends upon the column density and the temperature of the dust. As temperatures in IRDCs are around 10-20K (Peretto et al. 2010), the emission can be used to estimate the column density. As $\tau_{8\mu m}$ is also dependent on the column density, the opacity can be estimated and compared to Equation 2.1 to
2.2: FINDING THE OPACITY

give $I_{\text{fore}}$. This is discussed further in Section 2.5. By looking at the emission at 850\,$\mu$m, Johnstone et al. (2003) found that for the IRDC G11.11-0.12, the foreground and background emission were approximately equal. Peretto & Fuller (2009) looked at a wider sample of 57 starless cores (i.e. cores where the only emission is due to the dust) within 38 IRDCs using data at 1.2mm. They found that there is a relationship between the foreground and background emission given by

$$I_{\text{fore}} = 0.54I_{\text{MIR}}$$

(2.3)

where $I_{\text{MIR}} = I_{\text{fore}} + I_{\text{bg}}$ is equal to the total mid infrared radiation field i.e. the 8\,$\mu$m flux that would be received if the IRDC were not present. This is an intriguing result which suggests that most of the 8\,$\mu$m emission is local to the IRDCs. By using this empirical relationship, it is possible to separate $I_{\text{fore}}$ and $I_{\text{bg}}$ provided we can estimate the total mid infrared emission across the Galactic plane.

2.2.2 Creating the Opacity Maps

We estimate $I_{\text{MIR}}$ by applying a gaussian filter of FWHM 308” (or ~5’) to the 8\,$\mu$m data. This provides a good estimate of the structure of the 8\,$\mu$m emission on scales larger than 5’. The choice in FWHM is an important one; too large and the background will be under or overestimated in regions where the emission has a high gradient; too small and $I_{\text{MIR}}$ will drop significantly where there are IRDCs, causing IRDCs to either be missed or split into several objects as the lower density regions connecting the fragments are no longer detected. In addition, any fluctuation in 8\,$\mu$m with a length scale less than the smoothing length will be added to the SDC catalogue, a potential source of artefacts. 308” was chosen as it is the typical size of fluctuations at 8\,$\mu$m, is short enough to minimise the number of artefacts produced and long enough to prevent a significant drop in the $I_{\text{MIR}}$ at genuine IRDCs. Note that any IRDCs with a size larger than 5’ may be missed, particularly if they are not centrally condensed. Those that are...
centrally condensed will be detected but their opacity will be underestimated.

The GLIMPSEII data are contained in many tiles with a typical size of 0.25° × 2°. They lie across the Galactic plane at an angle so several tiles are present at each Galactic latitude. As a result there are many IRDCs that lie across more than one tile. To prevent any IRDCs being missed or truncated if they lie at the edge of a tile, we use the Montage software (http://montage.ipac.caltech.edu/) to mosaic several GLIMPSEII tiles together to create large blocks. These blocks cover the Galactic plane from $b = -1°$ to $1°$ and cover 1° in longitude. Each block overlaps its neighbours by 0.5° as the largest IRDC detected by [Simon et al.] (2006) had a major axis of 27′, so this overlap ensures that all IRDCs will be completely contained within a block.

Due to the high sensitivity of the GLIMPSEII data, a large number of point-like sources are detected, even at 8μm. As we are interested in small fluctuations in the mid infrared emission, these sources must be removed to prevent any stars inflating the estimates of $I_{\text{MIR}}$ or resulting in IRDCs being missed due to the presence of a foreground star. This was done by first identifying the stars using the IDL FIND routine; the pixels in the stars must then be replaced. We use the area surrounding the stars to find the typical background and the gradient of this background to replace the stars.

Once any point-like sources had been removed from the blocks, $I_{\text{MIR}}$ and $I_{\text{fore}}$ (using Equation 2.3) maps were found. $I_{\text{fore}}$ and $I_{\text{bg}} = I_{\text{MIR}} - I_{\text{fore}}$ could then be identified for each pixel. Equation 2.2 was then used to construct maps of 8μm opacity for each block to allow regions of high opacity to be identified as IRDCs. Figure 2.2 shows each stage of the process for obtaining the opacity maps for one SDC (SDC350.53+0.804) from the original 8μm map to the opacity map.

The main sources of uncertainty on the value of $\tau_{8\mu m}$ are due to uncertainties in the estimate of $I_{\text{fore}}$ and the variation in the background, with the variation in $I_{\text{fore}}$ likely
2.2: FINDING THE OPACITY

Figure 2.2: The different stages in the extraction process for SDC350.53+0.804. Left - the original 8μm data, Left Centre - I_{MIR}, Right Centre - the 8μm image with the point-like sources removed and I_{MIR} subtracted and Right: the 8μm opacity map of the SDC extracted.

dominating. In Section 2.5 we explore the relationship given in Equation 2.3 in more detail and find the standard deviation of the constant of proportionality is \( \sigma = 0.21 \). We therefore estimate that the error on \( \tau_{8\mu m} \) is around 25%.

2.2.3 Extracting the SDCs

An SDC was defined by Peretto & Fuller (2009) to be any structure in the opacity map where \( \tau_{8\mu m} > 0.35 \) with a peak \( \tau_{8\mu m} > 0.7 \). A minimum size of 4′′ × 4′′ was imposed as the resolution of the GLIMPSEII 8μm data are 2′′, so this is the minimum area required to ensure any dip in the mid infrared emission is not simply due to fluctuations within the errors of the data. The opacity map of each such object was extracted and added to the catalogue of SDCs. The catalogue also contains the original 8μm image of the SDC and its surrounding ‘field’, defined as a box surrounding the SDC with dimensions twice those of the SDC.

Some of the objects extracted in this way are artefacts. Artefacts can arise in several ways. As any dip in the mid infrared emission is identified using this method, some of the objects may simply be areas where there is less emission rather than regions
where the emission is being absorbed. In addition, the point-like source removal is not perfect; if any emission remains from the point-like sources, $I_{\text{MIR}}$ can increase in the surrounding area resulting in regions of high opacity surrounding the source. A final source of artefacts occurs when there is a steep gradient in the 8$\mu$m emission. Due to the long smoothing length used to find $I_{\text{MIR}}$, if the 8$\mu$m emission decreases dramatically in less than 5', a region of high opacity may appear along the edge of a bright feature. For this reason the gradient of $I_{\text{MIR}}$ at the position of each SDC has been included in the catalogue. The gradient of $I_{\text{MIR}}$, $\delta I_{\text{MIR}}$, is defined as $\delta I_{\text{MIR}} = (I_{\text{max, MIR}} - I_{\text{min, MIR}})/I_{\text{min, MIR}}$, where $I_{\text{max, MIR}}$ and $I_{\text{min, MIR}}$ are the maximum and minimum values of $I_{\text{MIR}}$ within the SDC respectively. During the by-eye examination of each SDC, we found that any SDC extracted from a region where $\delta I_{\text{MIR}} > 0.5$ is likely to be an artefact and should be treated with caution.

In order to minimise the number of artefacts in the catalogue, each object was checked by eye to remove any obviously false objects. These false objects are almost all be features surrounding very bright stars that have not been completely removed, and so have an edge the same shape as the diffraction pattern seen around bright stars. Artefacts caused by steep gradients in the background or dips in the background emission cannot be easily identified and so some artefacts remain in the catalogue. Figure 2.3 shows some of the SDCs that are not considered artefacts. With the advent of high resolution data from Herschel showing the IRDCs in emission, it has been possible to further investigate the validity of these SDCs (see Section 2.3).

In some cases the IRDCs may absorb all the background emission - they are saturated. In such cases it is impossible to determine the peak opacity and we can only give a lower limit. To identify which SDCs are saturated, we calculate the maximum opacity it is possible to measure towards each SDC, $\tau_{\text{sat}}$. In the case where the cloud is saturated, the maximum value $I_{\text{bg}} - I_{\text{fore}}$ would be the rms noise of the 8$\mu$m data, $\sigma_{\text{noise}} \sim 0.3$MJy/Sr. Thus Equation 2.2 becomes

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2.3: HERSCHEL COLUMN DENSITY MAPS

Figure 2.3: Three examples of SDCs extracted as described in the text. The images are 8µm intensity images with the stars removed and the contour shows the edge of the object extracted.

\[ \tau_{sat} = -\ln \left( \frac{\sigma_{noise}}{I_{bg}} \right). \]  

(2.4)

\( \tau_{sat} \) is calculated for each SDC at the opacity peak and is listed in the SDC catalogue. Any SDC with a peak opacity approaching \( \tau_{sat} \) should be considered to be saturated and the measured opacity of the peak should be treated with caution.

In total, 3317 SDCs were extracted in this way from the region \( |l| < 10^\circ, |b| < 1^\circ \). Due to a computing error in the extraction of SDCs in the original GLIMPSE region, 1017 SDCs were missed from the region \( 10^\circ < |l| < 65^\circ, |b| < 1^\circ \). Thus a total of 4334 new SDCs were extracted and added to the SDC catalogue. The original Spitzer 8µm image and the 8µm opacity map of each SDC is included in the catalogue, along with several properties of the SDCs. These properties are discussed further in Section 3.1

2.3 Herschel Column Density Maps

As previously discussed, some of the SDCs in the catalogue are not genuine objects. Many are simply ‘dips’ in the 8µm emission. Wilcock et al. (2012) compared the 250µm emission from the HiGAL survey with the SDC opacity maps by eye in the
region \( l = 300^\circ \) to \( l = 330^\circ \). They found that only 38% of the SDCs were ‘Herschel bright’ i.e. were seen in dust emission at 250\( \mu m \). In order to check whether this trend is representative of the Galactic plane and identify which SDCs are genuine, we construct column density maps using the 160 and 250\( \mu m \) data from the HiGAL survey and compare them with the opacity maps.

The flux received by the PACS and SPIRE instruments due to the emission from the dust is given by the grey-body equation (Equation 2.5)

\[
S_\nu = B_\nu(T_d)K_\nu \mu m_1 N_{\text{H}_2} \Omega_{\text{beam}},
\]

where \( B_\nu(T_d) \) is the Planck function

\[
B_\nu(T_d) = \frac{2h\nu^3}{c^2} \left( \frac{1}{e^{h\nu/kT} - 1} \right),
\]

\( T_d \) is the temperature of the dust, \( \Omega_{\text{beam}} \) is the solid angle subtended by the beam, \( K_\nu \) is the emission coefficient of the dust and gas, \( \mu \) is the mean molecular weight (taken to be 2.33) and \( N_{\text{H}_2} \) is the hydrogen column density. Figure 2.4 shows how the expected intensity of a cloud changes with wavelength. We can see that for a cloud with a temperature of 15K and a column density of \( 1 \times 10^{22} \text{ cm}^{-2} \) the 5 Herschel wavelengths cover the intensity peak. This is the case for temperatures between 7K and 35K, covering the expected temperature range of IRDCs (Peretto et al. 2010).

As we have data showing the SDCs in emission at 5 different wavelengths, it is possible to use Equation 2.5 to perform SED (or spectral energy distribution) fits, pixel by pixel, to find maps of the dust temperature and column density of the SDCs. We tested this method on an initial sample of SDCs from a single HiGAL tile (\( l = 30^\circ \)) to investigate whether such column density maps could be used to validate the SDCs and remove any
2.3: HERSHEY COLUMN DENSITY MAPS

Figure 2.4: Plot to show how the expected intensity of the dust emission changes with wavelength (Equation [2.5]) when the dust temperature is 15K and the column density is $1 \times 10^{22}$ cm$^{-2}$. The triangles show the expected intensity of the 70, 160, 250, 350 and 500µm data.

2.3.1 Performing SED Fits

SED fits were conducted for a small sample of SDCs. This sample was taken from the l=30° tile, as only the l=30° and l=59° tiles were available at the time this analysis was performed. We did not perform SED fits for the l=59° tile as there are no SDCs in this tile that meet the criteria required later in this Section. Whilst the emission data are available for 5 wavelengths, some SDCs are cold and dense enough to appear in absorption at 70µm. Hence we extract images of each SDC in the sample at the other 4 wavelengths (160, 250,350 and 500 µm) for the SED fits. The method and results described in this section are described in Peretto et al. (2010).

The emission in the Herschel bands seen from the direction of the SDCs consists of foreground and background emission as well as the emission from the SDC itself. In order to estimate how much emission comes from the SDC, we must first remove the artefacts.

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foreground and background emission. As in Section 2.2.2 we applied a gaussian of FWHM 5′ to provide an initial estimate of the background over large scales. However once the position of an SDC is known it is possible to recover more of the structure of the background emission by examining the emission from the surrounding pixels. Whilst the boundary has been defined in absorption as the area where $\tau_{8\mu m} > 0.35$, the lower resolution of the emission data requires the boundary to be redefined at 500 $\mu m$.

In emission, the distribution of the flux of the pixels in and surrounding an SDC appears as a peak with a high flux tail. This was used to define the SDC as those pixels with a flux greater than one standard deviation above the peak in this distribution (see Figure 2.5). The background can then be estimated within the SDC by applying an interpolation based on the nearest neighbours to estimate the flux of the background for each pixel. Each pixel within the SDC boundary was given a value found by taking the mean of the 5 closest pixels outside the SDC boundary. As shown in Figure 2.6, this method allows some of the structure in the background behind the SDC to be recovered. However, in regions where the emission fluctuates on a scale smaller than the size of an SDC, we may miss some structure, particularly towards the centre of the SDC. For this reason we exclude the W43 region of the $l = 30^\circ$ tile where the background emission is particularly complicated.

The Herschel data has different resolutions according to the wavelength (5′′, 12′′, 18′′, 25′′ and 36′′ at 70, 160, 250, 350 and 500 $\mu m$ respectively). In order to fit the data to Equation 2.5, the data must have the same resolution. If the data were to remain at their original resolutions, any peaks that are resolved at 160 $\mu m$ but not at 500 $\mu m$ would result in the flux ratio $S_{160} : S_{500}$ becoming artificially inflated, resulting in a lower dust temperature being calculated. Hence all the data and the background estimates are smoothed to a uniform resolution of 36′′. The background can then be subtracted from the data to leave just the emission from the SDCs at each wavelength (see Figure 2.6).
2.3: HERSCHEL COLUMN DENSITY MAPS

Figure 2.5: The flux distribution of the SDC and surrounding field of SDC30.143-0.069. The dashed line represents one standard deviation above the peak position, all pixels with a flux higher than this are considered to belong to the SDC.

The final images could then be used to perform a pixel-by-pixel SED fit. This was done by using the curve-fitting package MPFIT (Markwardt 2009) to fit the function shown in Equation 2.5 to the flux at each wavelength, taking $K_\nu = \kappa_\nu \nu^{-\beta}$, $\kappa_\nu = 0.12 \text{cm}^2 \text{g}^{-1}$ at 250$\mu$m and $\beta = 2$ (Hildebrand 1983). This constrains the dust temperature and column density for each pixel to provide maps of these properties (see Figure 2.6).

The initial tile chosen for this analysis ($l = 30^\circ$) contains $\sim$ 450 SDCs. However an initial inspection of these SDCs found that only around 80% were seen in emission (see Section 2.4 for a full discussion). In addition, many SDCs are smaller than 36'' and hence will not be resolved at 500$\mu$m. Hence a final sample of 22 SDCs with radii $> 36''$ outside the W43 region were chosen for this analysis.

The dust temperature maps have a median temperature of 15K and the coldest regions of the SDCs correlate with the column density peaks towards the centre of the clouds. The temperature maps reach temperatures as low as 8K and the temperature increases towards the edge of the clouds where they reach the temperature of the surrounding...
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Figure 2.6: Maps of SDC30.143-0.069; Top Left - the 8µm opacity map, Top Centre - the 500µm image with 5′ gaussian filter removed and a contour showing the boundary defined round the SDC, Top Right - as centre at 160µm, Bottom Left - the background found using the nearest neighbour interpolation, smoothed to 36′ resolution, Bottom Centre - the dust temperature map and Bottom Right - the column density map.

medium (20-30K). When this analysis was repeated with $\beta = 1.5$, the temperature only increased by around 2K, even in the coldest regions, hence our choice of $\beta$ does not greatly affect the temperatures found.
2.3.2 Ratio of 160:250\textmu m Emission

Whilst the SED fitting procedure described in Section 2.3.1 provides a robust method for finding dust temperature and column density maps of the SDCs, such analyses require significant computing time. As the SDC catalogue comprises of over 15,000 SDCs, a quicker method is required to find such maps for the entire catalogue.

Equation 2.5 contains two unknowns, the dust temperature, $T_d$ and the column density $N_{\text{H}_2}$. However, as we have data from several wavelengths, it is possible to reduce this to one unknown by taking the ratio of two of these wavelengths. As some SDCs appear as absorption features at 70\textmu m, we choose to use the 160 and 250\textmu m data for this, as they have the highest resolutions (12\arcsec and 18\arcsec) and so resolve smaller SDCs than at 500\textmu m. Hence taking the ratio of the flux of these two wavelengths ($R_{160/250}$) and letting $K_\nu = \kappa_\nu \nu^{-\beta}$ gives

$$R_{160/250} = \frac{B_{160}(T_d)}{B_{250}(T_d)} \left(\frac{250}{160}\right)^\beta.$$  (2.7)

This ratio is highly sensitive to temperature between 10 and 50K, the expected temperatures of IRDCs (see Figure 2.7). Hence by taking the ratio of the 160\textmu m data and the 250\textmu m data and again taking $\beta = 2$, we can obtain dust temperature maps. As when performing the SED fits, the data must first be smoothed to the same resolution, however as we are only using the 160\textmu m and 250\textmu m data we only need to smooth to a resolution of 18\arcsec. This allows dust temperature maps to be obtained at a resolution of 18\arcsec, much higher than the 36\arcsec of the temperature maps found in Section 2.3.1.

Whilst this method is less precise than the method described in Section 2.3.1 as we use only data at two wavelengths rather than five, the aim here is not to obtain accurate column density and temperature maps but to find column density peaks to confirm the existence of the SDCs. Nevertheless, the column density maps found are in good
Figure 2.7: Plot showing the variation of $R_{160/250}$, the ratio between 160$\mu$m to 250$\mu$m flux density as a function of dust temperature (see Eq. 2.7). The vertical dashed lines and plotted numbers highlight the values of $R_{160/250}$ for fiducial important dust temperatures. A value of 2 was adopted for the spectral index of the dust opacity law ($\beta$).

agreement with those found by taking an SED fit. Figure 2.8 shows the column density maps found using both methods and the fractional difference between the two is low at $\sim 0.1$. As such, taking the ratios allows a quick comparison between the opacity maps and column density maps. This method also provides column density maps at a resolution of 18", allowing us to check SDCs of a smaller radius than would be possible using a fit to the SED over the full range of wavelengths.

The uncertainty on the column densities obtained in this way come from two main sources; there are errors associated with the background estimates as any fluctuations on a scale less than 308" are not considered and there are additional errors resulting from using the ratio method and not SED fits to estimate the temperature and hence the column density. The uncertainties due to background fluctuations can be estimated by considering the typical fluctuations in the background. Figure 2.9 shows the distribution of the column density in a 5' by 5' box in the l=30° tile, with a gaussian representing the size of the fluctuations in the background. The dispersion of the gaussian in Figure 2.9 is 27.6cm$^{-2}$ and by examining similar histograms across the galactic plane,
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Figure 2.8: The cloud SDC4.511-0.244 shown at: Left - 250µm, Left Centre - Herschel column density at 18′′ resolution, Right Centre - Herschel column density at 36′′ resolution computed using an SED fit and Right - the fractional difference (N$_{18}$ − N$_{36}$)/N$_{36}$ between the two column density maps (with the 18′′ map smoothed to 36′′). The contours are the same in all images and are the 250µm contours from 1750 to 1950MJy/Sr in steps of 50MJy/Sr.

we estimate the uncertainty in the column density due to background fluctuations is around 20%. The uncertainty due to the method used is around 10% as described in the previous paragraph. Hence we estimate that the total uncertainty in the column density is 25%.

Dust temperature maps were found for each HiGAL tile in this way. These were then converted to column density maps using Equation 2.5. As before, some of the column density is from the dust along the line of sight to the cloud. This background was removed in the same way as the background 8µm emission was removed from the GLIMPSE tiles; by applying a 5′ gaussian to the column density maps and subtracting this from the column density maps to remove any structure on a scale larger than 5′.

In order to determine whether the column density peaks are consistent with the opac-
Figure 2.9: Histogram of the intensity of the pixels in a 5′ box around a pixel in the \( l = 30° \) tile with a 5′ gaussian filter subtracted. The negative part of the histogram has been reflected about \( x=0 \) (dashed line) and a gaussian fitted (see text).

ity maps of the SDCs, we need only determine whether these peaks are significant compared to small-scale fluctuations in the background. We use the method developed by Battersby et al. (2011) to characterise these background fluctuations. Once the 5′ gaussian filter had been subtracted, we take a 5′ box around each pixel of the resulting column density map. A histogram of the column density of each box was drawn and found to contain two main components; a high-flux tail due to any sources within this box and a gaussian distribution centred at \( x=0 \) due to the typical fluctuations of the background. This second component can be characterised by the pixels with negative column densities, as no sources have negative column densities, and so the noise distribution can be recovered by reflecting the negative side of the histogram peak in the y-axis (see Figure 2.9). A gaussian was then be fitted to this distribution and the dispersion found to provide a dispersion map of each tile.

The column density map is divided by the dispersion maps to obtain ‘signal-to-noise’ (\( \sigma \)) maps for each tile. Smaller maps were then extracted from these tiles for each SDC along with its surrounding field to ensure a comparison with the surrounding medium
2.4: Confirming the SDCs

We can now look at the signal-to-noise maps to confirm whether the 8µm opacity peaks correspond to column density peaks. To do this we must first identify the peaks in the signal-to-noise maps. This was done using the clump-finding algorithm designed in Peretto & Fuller (2009) to find ‘fragments’ (peaks in the opacity maps see Section 3.1.2).

The algorithm first applies contours to the signal-to-noise maps, starting with the lowest contour at a column density, $N_{\text{thresh}}$, below which we consider any structure to be insignificant. The step between each contour, $N_{\text{step}}$, will impact the number of peaks identified and so this value must be chosen carefully. A mask is created of the peaks can be made.

Figure 2.10: The ‘signal-to-noise’ map of SDC30.143-0.069 found by dividing the column density by the dispersion map. The contours are drawn from $N_{\text{thresh}} = 1.5\sigma$ with $N_{\text{step}} = 0.5\sigma$. 

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defined by the top contour. For each peak, we look at the next contour down and create a second mask. If the peak is the only one within the mask of the lower contour, the next contour down is examined until $N_{\text{thresh}}$ is reached. If a second peak appears in the second mask, we look for the local minimum between the two peaks. Figure 2.11 shows how the contours are applied to a structure and the local minimum determined. Any pixels associated with the peak being examined and lying above this local minimum are defined as belonging to the peak. Any peak which does not have a height above this local minimum of $N_{\text{step}}$ is considered not to be significant and we do not consider any peaks that are smaller than the resolution of the images (18′′). This leaves us with a mask showing each peak at the lowest contour for which the peak is unique.

In many cases, particularly for the smaller SDCs, there is only one column density peak resolved in each cloud, often this peak is larger than the SDC due to the lower resolution of the HiGAL data. For this reason, we don’t simply look at the mask of the peaks to see whether they lie within the limits of the SDC, we instead look at the highest contour level at which the peak remains larger than 18′′. The shaded regions in Figure 2.11 show the contour level at which the peaks are considered. The mask of this contour level is taken and this is compared to the opacity map of the SDC. We consider an SDC to be real if 50% of a peak found in this way lies within the limits of the SDC (i.e. within the region where $\tau_{\text{sum}} > 0.35$). We only require 50% of the peak to lie within the SDCs as the resolution of the opacity maps is 2.4′′ and hence the peak in the signal-to-noise map may appear near the edge of the SDC. This percentage was chosen empirically as described in the next paragraph.

The parameters used in this analysis were chosen carefully. We chose a sample of 206 SDCs comprising of all the SDCs in the regions $l = 301 - 303^\circ$ and $l = 5 - 6^\circ$. These two regions were chosen as these regions have very different background conditions, with high levels of emission towards the Galactic centre and much lower emission to-
Figure 2.11: Demonstration of the clump-finding algorithm. The dotted lines show the contour lines applied from $N_{\text{thresh}} = 1.5\sigma$ with $N_{\text{step}} = 0.5\sigma$. The dashed line shows the local minimum between the two peaks and the solid lines shows the contour level at which the mask of the peaks is taken for comparison with the opacity map. The shaded regions show the resulting peaks that are compared with the opacity map.

Towards the edge of the Galactic plane. The HiGAL and column density images for each of these SDCs were examined by eye to decide which were genuine SDCs and which were artefacts. Figure 2.12 shows some examples illustrating which SDCs are considered real and which are not. Those SDCs that appear to have a column density peak of similar size and shape to the SDC extracted from the opacity maps are considered real. In some cases, such as that shown in Figure 2.12(b), the SDC may be part of a larger structure although there is not column density peak. These SDCs are not considered real as they do not meet our criteria for a ‘real’ SDC. The parameters that gave the same results to this by-eye comparison were $N_{\text{step}} = 0.5\sigma$ and $N_{\text{thresh}} = 1.5\sigma$, meaning that any peak must have a minimum height of $2\sigma$ to be considered significant.

As the resolution of the signal-to-noise maps is $18''$, some of the smaller SDCs may not be detectable. In order to investigate the detection limit, several SDCs, with radii between $5''$ and $60''$ and peak column densities as close to $\tau_{8.0\text{um}} = 0.7$ as possible, were
2: COMPLETING AND CLEANING THE SPITZER DARK CLOUD CATALOGUE

Figure 2.12: An example one SDC considered real (a) and two considered not to be real (b & c). (a) is considered real as it has a column density peak that closely matches the size and shape of the SDC. (c) does not have a column density peak within the limits of the SDC. (b) is not considered real as it does not have a column density peak within the limits of the SDC, however it may be part of a larger structure.

chosen as test SDCs. SDCs with low column densities were chosen as these would have the lowest column density and thus be the most difficult to detect. The opacity maps of these SDCs were converted into column density maps using the relation $N_{\text{H}_2} = \tau_{8\mu m} \times 3 \times 10^{22} \text{cm}^{-2}$ (Peretto & Fuller 2009). These simulated column density maps were superimposed onto two higal tiles in 15 different places at different Galactic longitudes and latitudes. The tiles chosen were $l = 0^\circ$ and $l = 61^\circ$ as the $l = 0^\circ$ tile represents the brightest background conditions in the galaxy and the $l = 61^\circ$ tile represents some of the lowest background column densities. The SDC detection algorithm was then applied to these tiles to see if these test SDCs could be detected. We found that even...
in the brightest regions, any SDC with a radius larger than 20″ could be detected and in regions with lower background, all SDCs could be detected. We estimate that any SDC can be detected in regions with a background column density less than $10^{22}\text{cm}^{-2}$.

2.4.1 Results

Of the 15,637 SDCs extracted from the 8μm GLIMPSE and GLIMPSEII tiles, 8113 had corresponding Herschel column density peaks. Of the 8369 SDCs with an equivalent radius greater than 20″, 58% were detected whereas only 45% of the SDCs smaller than 20″ were detected. The SDCs smaller than 20″ may not be detected due to the lower resolution of the Herschel data, so it is likely that in reality, 58% of these objects are indeed real. In addition, as demonstrated in Figure 2.12(b), some of the undetected objects may be genuine, but part of larger structures.

Figure 2.13(a) shows how the detection rate changes with SDC size. For SDCs with an equivalent radius of 20″ to 200″, the detection rate varies between 50% and 70%. The detection rate falls below 50% for the largest SDCs as the 5′ gaussian filter used to remove the background from the 8μm tiles can create large artefacts alongside bright emission features (see Section 2.2.3).

The rate of detection is not constant across the Galactic plane (see Figure 2.13(b)). The detection rate is highest towards the centre of the galaxy and decreases towards the edge of the Galactic plane. In the region $|l| < 40°$ the detection rate remains between 50% and 80% and drops significantly outside this region. This is mainly because the 8μm background emission is lower towards the edge of the galaxy and so a smaller ‘dip’ in the background would be required to create an artefact. Wilcock et al. (2012) found that only 38% of the SDCs in the region $l = 300°$ to $330°$ could be seen in emission at 250μm. We find that even though it may not be possible to see the smaller SDCs in column density and we have excluded SDCs that may belong to
Figure 2.13: (a) Histogram showing how the percentage of SDCs detected (shaded, left axis) changes with the size of the SDCs. The dashed line shows the limit of 20″ above which we would expect to be able to detect all SDCs. (b) Histogram showing how the percentage of SDCs detected with a radius \( > 20″ \) (shaded, left axis) changes with Galactic longitude. The total number of SDCs in each bin is shown as an unshaded histogram using the right axis in each case.

larger structures but do not have column density peaks, the detection rate in this region is, larger than the results of Wilcock et al. (2012).

2.5 Confirming I_{\text{fore}}

When calculating the 8\( \mu \)m opacity in Section 2.2 we used the empirical relationship \( I_{\text{fore}} = 0.54I_{\text{MIR}} \) to constrain the foreground emission in front of each SDC. This relationship was found by comparing the emission and absorption of a sample of 38 SDCs in Peretto & Fuller (2009). A similar result was found by Johnstone et al. (2003) by looking at each pixel in one IRDC. However now that we have data showing a large sample of SDCs in both emission and absorption, it is possible to investigate the validity of this relationship across a larger sample and hence constrain the errors in our estimates of \( \tau_{8\mu m} \).
The foreground emission can be calculated from $\tau_{8\mu m}$ by rearranging Equation 2.2 and letting $I_{bg} = I_{MIR} - I_{fore}$ to obtain the expression

$$I_{fore} = \frac{I_{8\mu m} - I_{MIR}e^{-\tau_{8\mu m}}}{1 - e^{-\tau_{8\mu m}}}. \quad (2.8)$$

$\tau_{8\mu m}$ can be estimated from the dust emission by using the relationship $\tau_{8\mu m} = N_{H_2}/3 \times 10^{22}$ given by Peretto & Fuller (2009). As $I_{MIR}$ maps have already been obtained as described in Section 2.2.2, $I_{fore}$ can be estimated for each pixel in an SDC from the column density maps obtained in Section 2.3.2. $I_{8\mu m}$ was found by smoothing the Spitzer $8\mu m$ tiles to the same resolution as the Herschel column density maps (18$''$).

In order to ensure that we obtain good estimates for $I_{fore}$, we choose to calculate $I_{fore}$ for the ‘dark’ pixels only. We define a ‘dark’ pixel as one where the fractional difference between $I_{MIR}$ and $I_{8\mu m}$ is greater than 0.1 i.e. where

$$\frac{I_{MIR} - I_{8\mu m}}{I_{MIR}} > 0.1. \quad (2.9)$$

If less than 10% of the pixels in an SDC meet this requirement, we took the darkest pixels so that at least 10% of each SDC was analysed. This ensured that $I_{fore}$ was not unduly influenced by a single pixel whilst still constraining the calculation of $I_{fore}$ to the darkest part of each SDC. $I_{fore}$ is then divided by $I_{MIR}$ to find the fraction of the emission along the line of sight that comes from the foreground.

We take the median and dispersion of the distribution of $I_{fore}/I_{MIR}$ for each SDC detected in Herschel column density (see Figure 2.14(a)). $I_{fore}$ is well constrained across the clouds and in most cases the dispersion is small. Figure 2.14(b) shows a histogram of the $I_{fore}$ estimates for all the detected SDCs. This histogram peaks at 0.6 and has a
2: COMPLETING AND CLEANING THE SPITZER DARK CLOUD CATALOGUE

Figure 2.14: (a) Histogram of the ratio I_{\text{fore}}/I_{\text{MIR}} for the 40 darkest pixels in SDC4.511-0.244 and (b) Histogram of the median I_{\text{fore}}/I_{\text{MIR}} ratio each SDC detected in the Herschel derived column density with equivalent radius > 20".

The median value of 0.52, essentially the same result as found by Peretto & Fuller (2009); Johnstone et al. (2003). The interpretation of this result by these authors is that as the foreground and background emission is approximately equal for the SDCs, suggesting that the 8μm emission is emitted from the locality of the IRDCs. Note that several SDCs have a fraction I_{\text{fore}}/I_{\text{MIR}} > 0.7, these SDCs should be treated with caution as in these cases I_{\text{fore}} is approaching I_{8\mu m}. These SDCs are therefore approaching saturation, where all the background emission is absorbed by the cloud and I_{\text{fore}} = I_{8\mu m}.

As we have calculated I_{\text{fore}} for over 8000 SDCs across the Galactic plane, we can investigate how the relationship between I_{\text{fore}} and I_{\text{bg}} changes throughout the Galactic plane. Figure 2.16 shows how the fraction I_{\text{fore}}/I_{\text{MIR}} varies with Galactic latitude and longitude. In longitude, the fraction rises towards the Galactic centre. We might expect this to be because the background emission is brighter, meaning a larger dip in
Figure 2.15: Plot showing how the detection rate changes with the brightness of the background. We take the average value of $I_{\text{MIR}}$ in the field surrounding each SDC and plot the percentage of SDCs detected in each bin.

the background is necessary to result in the false detection of an SDC. We investigate this in Figure 2.15 where we plot the percentage of SDCs that are detected against the brightness of the background emission at 8$\mu$m ($I_{\text{MIR}}$). This shows that a lower percentage of SDCs are detected in regions with the brightest 8$\mu$m emission. This may be because the brightest regions tend to be regions of active star formation and as a result they have 8$\mu$m emission that fluctuates on a scale less than 308", resulting in a larger number of artefacts due to dips in the emission. We may detect fewer SDCs in the outer part of the Galactic plane there may be regions of very low background at 8$\mu$m, resulting in very small fluctuations in the background being falsely extracted as an SDC. There is a slight increase in the detection rate in latitude towards the plane of the galaxy for the same reason.

With individual estimates of the ratio between $I_{\text{MIR}}$ and $I_{\text{fore}}$ for each SDC, it is possible to re-calculate $\tau_{8\mu m}$ with a more accurate estimate of $I_{\text{fore}}$. As the 8$\mu$m data has a
Figure 2.16: Distribution of the mean ratio $I_{\text{fore}}/I_{\text{MIR}}$ across each cloud as a function of Galactic latitude (a) and Galactic longitude (b). The error bars show the dispersion in the ratio within each bin.

resolution of 2.4′′, the intensity at the opacity peaks will be reduced in the 18′′ images. As a result there are 1379 SDCs for which $I_{\text{fore}} > I_{8\mu m}$ for the densest parts of the clouds (these SDCs are most likely to be saturated). Nevertheless, where possible, $\tau_{8\mu m}$ has been recalculated and the peak $\tau_{8\mu m}$ is given with the SDC catalogue. The main source of uncertainty on these recalculated values of $\tau_{8\mu m}$ is the uncertainty in $I_{\text{fore}}$, which in turn depends on the uncertainty in the column density of 25%. This translates to an uncertainty of around 30% in the estimates of the recalculated peak $\tau_{8\mu m}$.

2.6 Summary

The SDC catalogue has been extended to include the central region of the Galactic plane ($|l| < 10^\circ, |b| < 1^\circ$), adding a further 3317 objects to the catalogue. A further 1017 SDCs were added in the region covered by the original survey that were missed due to a computing error. Opacity maps for each of these objects have been found and the peak and average opacities for each object identified. This brings the total number
of objects in the SDC catalogue to 15,637 objects in the region (|l| < 65°, |b| < 1°).

*Herschel* column density and temperature maps for the Galactic plane have been obtained using the ratio between the flux at 160\(\mu\)m and 250\(\mu\)m (\(R_{160/250}\)). The typical fluctuations in the column density have been characterised to create dispersion maps and hence ‘signal-to-noise’ maps by dividing the column density by the dispersion maps. These maps have allowed column density peaks to be identified and associated with the SDCs, allowing the SDCs with no such associated column density peak to be identified as artefacts. These artefacts are likely to be ‘dips’ in the 8\(\mu\)m emission falsely extracted as objects rather than true IRDCs. This has provided a catalogue of 8113 SDCs that have associated column density peaks. Due to the lower resolution of the 250\(\mu\)m data, it is possible that any SDC with a radius less than 20′′ may have a column density peak that cannot be observed.

The relationship between the foreground and background emission has been investigated by comparing the emission and absorption of the SDCs. This has confirmed that the empirical relationship \(I_{\text{fore}} = 0.54I_{\text{MIR}}\) is a good approximation across all regions in the Galactic plane. The fraction \(I_{\text{fore}}/I_{\text{MIR}}\) has been found for each SDC and \(\tau_{8\mu m}\) has been recalculated using this fraction. We are unable to recalculate \(\tau_{8\mu m}\) for those SDCs for which \(I_{\text{fore}}\) is approximately equal to the minimum 8\(\mu\)m emission towards the SDC. This has allowed 1379 of the SDCs with associated column density peaks to be identified as saturated.

With the SDC catalogue completed and a higher level of confidence in the 8113 SDCs with column density peaks, it is now possible to examine the properties of the SDCs in an aim to further understand the initial conditions of star formation.
SDC Analysis

The Galactic centre is the most dynamic place in the galaxy. The molecular clouds in the Galactic centre are subject to very different conditions than those in the Galactic plane. There is non-circular motion of the gas due to the potential of the Galactic bar, causing collisions between molecular clouds (Binney et al. 1991). There are strong mG magnetic fields present, which could favour massive star formation (Güsten & Philipp 2004). There is also a temperature discrepancy between the gas (75 - 200 K) and dust (< 30 K), which suggests the molecular gas is being heated directly eg. by shocks or cosmic rays (Lis et al. 2001).

These conditions have a direct impact on the properties of the molecular clouds near the Galactic centre. A study of the velocity linewidths of the Galactic centre molecular clouds by Miyazaki & Tsuboi (2000) revealed that they are ~ 5 times more turbulent than clouds of equivalent size in the Galactic plane. Miyazaki & Tsuboi (2000) also found the virial masses of the molecular clouds are greater than the observed masses, suggesting an external influence (e.g. strong magnetic fields) is required to bind the clouds.

An interesting feature of the central molecular zone of the galaxy is an elliptical ring of cold dust surrounding the Galactic centre (Molinari et al. 2011). This ring includes the
star forming regions Sagittarius B2 and Sagittarius C, both active sites of star formation, although there is little evidence of star formation elsewhere in the ring. This ring shows several absorption features at 70µm indicating the presence of IRDCs within this ring. One of these IRDCs is G0.253+0.016 (SDC0.341+0.095), an extremely large and dense IRDC with little evidence of current star formation (Longmore et al. 2011). It is thought that this IRDC may be a precursor to a massive stellar cluster and is the most massive IRDC known to date, with a mass of 10^5M_☉. As this IRDC is associated with the central molecular zone, it may be that the conditions present here have enabled such a dense IRDC to form. By examining the properties of the IRDCs towards the Galactic centre, it may be possible to identify whether these IRDCs are affected by their surroundings and how this may influence star formation.

3.1 Properties of the SDCs

The SDC catalogue is not merely a series of images of the IRDCs identified in the Galactic plane. Included with the 8µm images and 8µm opacity maps in the SDC catalogue are several of the properties of the SDCs (see Tables 3.1 Peretto & Fuller (2009)). Now that we have 4334 additional SDCs to add to the catalogue, these properties must be found for the new SDCs. The properties of the SDCs in different regions can then be analysed to find trends that could give insight into their role in star formation.

3.1.1 Observed Properties

Some of the properties in the SDC catalogue are simple to find from the opacity map and 8µm image. The maximum opacity within the SDC, τ_{peak}, and the average opacity within the cloud, τ_{av}, are listed in the catalogue. The minimum 8µm emission and the mean value of I_{MIR} observed within the SDC are also listed. The gradient of I_{MIR}, δI_{MIR}, and the maximum detectable opacity before the cloud becomes saturated, τ_{sat},
are found as described in Section 2.2.3 to provide information on whether the SDC is likely to be an artefact or if it is likely to be saturated. Also listed with the SDC catalogue is the equivalent radius, major and minor axes and position angle of the major axis w.r.t. north. These properties cannot simply be read from the opacity map or 8µm image and must be calculated.

The equivalent radius provides an estimate of the size of the SDCs and is defined as the radius the SDC would have if it were circular. The equivalent radius is therefore found by taking the area of the SDC and taking \( R_{eq} = \sqrt{A/\pi} \). Due to the complicated shapes of the SDCs, the major and minor axes are less simply defined. However, when we diagonalise the matrix of the moment of inertia, the eigenvectors give the directions of the major and minor axes. To find the moment of inertia, first we must find the centre of gravity of the SDCs. The centre of gravity is given by

\[
X_{CG} = \frac{\sum_{i=1}^{N} \tau_i x_i}{\sum_{i=1}^{N} \tau_i} \quad \text{and} \quad Y_{CG} = \frac{\sum_{i=1}^{N} \tau_i y_i}{\sum_{i=1}^{N} \tau_i} \quad \text{(3.1)}
\]

where \( x_i \) and \( y_i \) are the coordinates of the pixels. Hence the matrix of inertia is given by

\[
I = \begin{pmatrix}
I_{xx} & I_{xy} \\
I_{yx} & I_{yy}
\end{pmatrix} \quad \text{(3.2)}
\]

where

\[
I_{xx} = \sum_{i=1}^{N} \tau_i (x_i - X_{CG})^2 \quad \text{(3.3)}
\]

\[
I_{yy} = \sum_{i=1}^{N} \tau_i (y_i - Y_{CG})^2 \quad \text{(3.4)}
\]

\[
I_{xy} = I_{yx} = \sum_{i=1}^{N} \tau_i (x_i - X_{CG})(y_i - Y_{CG}). \quad \text{(3.5)}
\]
Once we have the moment of inertia matrix for an SDC, we find the eigenvalues and eigenvectors. The eigenvector associated with the smallest eigenvalue gives the direction of the major axis. The position angle, $\alpha$, can then be found by taking the angle between this eigenvector and north. We define the position angle as the angle east of north, giving it a value $-90^\circ < \alpha < 90^\circ$. The major and minor axes, $\Delta X$ and $\Delta Y$, are then given by taking the root mean square distance of each pixel within the SDC along these eigenvectors to give the semi-major and semi-minor axes i.e. by taking

$$\sigma_x^2 = \sum_{i=1}^{N} [(x_i \cos(\alpha) - y_i \sin(\alpha)) - [X_{CG} \cos(\alpha) - Y_{CG} \sin(\alpha)]^2$$  \hspace{1cm} (3.6)$$

$$\sigma_y^2 = \sum_{i=1}^{N} [(x_i \sin(\alpha) + y_i \cos(\alpha)) - [X_{CG} \sin(\alpha) + Y_{CG} \cos(\alpha)]^2$$  \hspace{1cm} (3.7)$$

$$\Delta X = 2 \sqrt{\frac{\sigma_x^2}{N}} \quad \Delta Y = 2 \sqrt{\frac{\sigma_y^2}{N}}. \hspace{1cm} (3.8)$$

These properties were identified for the 4334 new SDCs found in Chapter 2 and added to the SDC catalogue. However as we now also have Herschel column density maps of the SDCs, we are able to find some other properties of the SDCs. Due to the difference in resolution between the column density maps and the opacity maps, we do not give the peak column density as the lower resolution would cause this to be lower than the estimates from the opacity map. We do, however, include the mean column density of the SDCs. Also given is whether or not the SDC is detected in the column density to dispersion ratio maps (see Section 2.4), the fraction $I_{\text{fore}}/I_{\text{MIR}}$, whether or not the SDC is approaching saturation (i.e. whether $I_{\text{fore}}$ is approaching $I_{8\mu m}$) and the peak opacity calculated using this fraction (see Section 2.5). We can also use the temperature maps found in Section 2.3.2 to find the median temperature within the SDCs. In some cases it was not possible to estimate these properties. If the SDC is not detected in Herschel column density, the average column density cannot be given and if the SDC is approaching saturation the peak opacity cannot be recalculated using the $I_{\text{fore}}/I_{\text{MIR}}$. 

Clouds and Filaments
3.1: PROPERTIES OF THE SDCS

3.1.2 Fragments

If the SDCs are the earliest stages in star formation, they will need to fragment in order to collapse under gravity into star-forming cores. Evidence of this fragmentation can be seen in some of the SDCs as the opacity maps contain more than one opacity peak, indicating the presence of several regions of high density (see Figure 3.1). We are able to characterise the fragmentation of the SDCs by identifying the different opacity peaks using the clump-finding algorithm described in Peretto & Fuller (2009) and in Section 2.4. These different opacity peaks are called ‘fragments’ by Peretto & Fuller, rather than ‘clumps’ or ‘cores’, as it is not clear whether these opacity peaks will lead to the formation of stars, star clusters or nothing at all.

As previously discussed, the clump-finding algorithm applies contours to the opacity map from an initial opacity, $\tau_{\text{thresh}}$, to the maximum opacity with a step between the
contours of $\tau_{\text{step}}$. Any local peaks are identified at each contour level, starting from $\tau_{\text{thresh}}$ up to the highest contour level. The number of local peaks gives the number of fragments. The size and shape of the fragments can then be found by comparing the mask of the local peak at its highest contour with the mask of that peak in the next contour down. If the peak remains unique at the lower contour level, the next peak down is considered until an additional peak appears in the mask or $\tau_{\text{thresh}}$ is reached. If an additional peak appears in the mask, we find the local minimum in the opacity between the two peaks. The fragment then contains any pixels associated with the peak with an opacity greater than this local minimum. In the case where there is only one opacity peak, the fragment will have the same shape as the SDC. The number of fragments is given with the SDC catalogue in Table 3.1. In addition to the number of fragments, the major and minor axes and the peak and average opacities of the fragments are found in the same way as these properties were found for the SDCs themselves.

3.2 Distribution of SDCs

IRDCs are clearly a common feature across the Galactic plane; 8113 SDCs have been associated with column density peaks across the Galactic plane. However the conditions under which IRDCs form is still unclear. By looking at the distribution of SDCs in the Galactic plane, it may be possible to find the conditions under which IRDCs are most likely to form. For example we might expect to observe more SDCs in regions of high 8$\mu$m emission, either because regions that are bright at 8$\mu$m represent star forming regions where IRDCs may be likely to form or because a bright background will make it easier to detect more diffuse IRDCs. Figure 2.15 shows that there are fewer false SDCs in less bright regions, most likely as the brightest regions tend to have the greatest fluctuations in the background emission, so the number of small, undetected SDCs that are false may increase in these regions.
Table 3.1: Properties of a sample of objects in the Spitzer dark cloud (SDC) catalogue.

<table>
<thead>
<tr>
<th>Name</th>
<th>Coordinates</th>
<th>( I_{\text{min}} )</th>
<th>( I_{\text{MIR}} )</th>
<th>( \delta I_{\text{MIR}} )</th>
<th>( \Delta X )</th>
<th>( \Delta Y )</th>
<th>( \alpha )</th>
<th>( R_{eq} )</th>
<th>( \tau_{\text{peak}} )</th>
<th>( \tau_{av} )</th>
<th>( \tau_{sat} )</th>
<th>Frag</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDC9.004-0.304</td>
<td>271.72</td>
<td>-21.29</td>
<td>26.94</td>
<td>41.45</td>
<td>0.206</td>
<td>208</td>
<td>66</td>
<td>64</td>
<td>79.0</td>
<td>1.39</td>
<td>0.50</td>
<td>4.15</td>
</tr>
<tr>
<td>SDC9.01-0.53</td>
<td>271.93</td>
<td>-21.38</td>
<td>22.87</td>
<td>34.54</td>
<td>0.124</td>
<td>121</td>
<td>91</td>
<td>-19</td>
<td>94.1</td>
<td>1.33</td>
<td>0.61</td>
<td>3.97</td>
</tr>
<tr>
<td>SDC9.032-0.188</td>
<td>271.62</td>
<td>-21.23</td>
<td>43.65</td>
<td>57.55</td>
<td>0.013</td>
<td>42</td>
<td>12</td>
<td>-80</td>
<td>20.7</td>
<td>0.75</td>
<td>0.42</td>
<td>4.48</td>
</tr>
<tr>
<td>SDC9.059-0.275</td>
<td>271.70</td>
<td>-21.24</td>
<td>36.27</td>
<td>48.34</td>
<td>0.022</td>
<td>17</td>
<td>10</td>
<td>52</td>
<td>14.3</td>
<td>0.78</td>
<td>0.46</td>
<td>4.31</td>
</tr>
<tr>
<td>SDC9.127-0.302</td>
<td>271.76</td>
<td>-21.21</td>
<td>34.94</td>
<td>47.23</td>
<td>0.033</td>
<td>32</td>
<td>23</td>
<td>-82</td>
<td>26.2</td>
<td>0.83</td>
<td>0.45</td>
<td>4.28</td>
</tr>
<tr>
<td>SDC9.129-0.374</td>
<td>271.83</td>
<td>-21.24</td>
<td>31.37</td>
<td>41.95</td>
<td>0.020</td>
<td>26</td>
<td>25</td>
<td>-2</td>
<td>26.0</td>
<td>0.79</td>
<td>0.43</td>
<td>4.16</td>
</tr>
<tr>
<td>SDC9.132+0.149</td>
<td>271.34</td>
<td>-20.98</td>
<td>33.63</td>
<td>46.86</td>
<td>0.060</td>
<td>103</td>
<td>26</td>
<td>-87</td>
<td>51.4</td>
<td>0.95</td>
<td>0.50</td>
<td>4.28</td>
</tr>
<tr>
<td>SDC9.134-0.178</td>
<td>271.66</td>
<td>-21.12</td>
<td>38.50</td>
<td>50.80</td>
<td>0.074</td>
<td>80</td>
<td>33</td>
<td>21</td>
<td>41.0</td>
<td>0.72</td>
<td>0.41</td>
<td>4.36</td>
</tr>
<tr>
<td>SDC9.147+0.041</td>
<td>271.46</td>
<td>-21.02</td>
<td>43.69</td>
<td>60.44</td>
<td>0.024</td>
<td>24</td>
<td>12</td>
<td>-23</td>
<td>17.8</td>
<td>0.92</td>
<td>0.55</td>
<td>4.53</td>
</tr>
<tr>
<td>SDC9.151+0.03</td>
<td>271.47</td>
<td>-21.02</td>
<td>43.63</td>
<td>62.38</td>
<td>0.017</td>
<td>14</td>
<td>8</td>
<td>-41</td>
<td>11.9</td>
<td>1.06</td>
<td>0.52</td>
<td>4.56</td>
</tr>
</tbody>
</table>

The columns give (1) the name of the cloud, (2,3) the J2000 right ascension and declination of the peak of the cloud, (4) the minimum 8\( \mu \)m emission towards the cloud \( I_{\text{min}} \), (5) the 8\( \mu \)m emission \( I_{\text{MIR}} \), (6) the maximum \( I_{\text{min}} \) variation within the IRDC \( \delta I_{\text{min}} \), (7,8), the size of the cloud along its major and minor axes in arcseconds, (9), the position angle of the major axis of the cloud in degrees East of North, (10) the equivalent radius \( R_{eq} \) of the cloud, (11) the peak and average optical depth of the cloud at 8\( \mu \)m, (12,13) the optical depth at 8\( \mu \)m at which the absorption would be saturated and (14) the number of fragments in the cloud identified with \( \tau_{\text{step}} = 0.35 \).
Table 3.2: *Herschel* related properties of a sample of objects in the Spitzer dark cloud (SDC) catalogue.

<table>
<thead>
<tr>
<th>Name</th>
<th>Herschel detected</th>
<th>$I_{\text{fore}}/I_{\text{MIR}}$ Fraction</th>
<th>$I_{\text{fore}}/I_{\text{MIR}}$ Limit</th>
<th>Average Column Density (10$^{22}$ cm$^{-2}$)</th>
<th>Recalculated Peak $\tau_{8\mu m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDC9.004-0.304</td>
<td>yes</td>
<td>0.64</td>
<td>no</td>
<td>1.89</td>
<td>3.35</td>
</tr>
<tr>
<td>SDC9.01-0.53</td>
<td>yes</td>
<td>0.77</td>
<td>yes</td>
<td>6.25</td>
<td></td>
</tr>
<tr>
<td>SDC9.032-0.188</td>
<td>yes</td>
<td>0.44</td>
<td>no</td>
<td>0.77</td>
<td>0.56</td>
</tr>
<tr>
<td>SDC9.059-0.275</td>
<td>yes</td>
<td>0.70</td>
<td>no</td>
<td>1.31</td>
<td>1.76</td>
</tr>
<tr>
<td>SDC9.127-0.302</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDC9.129-0.374</td>
<td>yes</td>
<td>0.42</td>
<td>no</td>
<td>0.72</td>
<td>0.57</td>
</tr>
<tr>
<td>SDC9.132+0.149</td>
<td>yes</td>
<td>0.68</td>
<td>no</td>
<td>1.85</td>
<td>2.14</td>
</tr>
<tr>
<td>SDC9.134-0.178</td>
<td>yes</td>
<td>0.52</td>
<td>no</td>
<td>0.94</td>
<td>0.68</td>
</tr>
<tr>
<td>SDC9.147+0.041</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDC9.151+0.03</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The columns give (1) the name of the cloud, (2) whether the SDC is detected in the *Herschel* column density map, (3) the fraction of the total 8$\mu$m radiation field represented by the foreground emission ($I_{\text{fore}}/I_{\text{MIR}}$), (4) whether the calculated $I_{\text{fore}}/I_{\text{MIR}}$ is greater than the upper limit calculated assuming all 8$\mu$m emission at the peak of the cloud is foreground emission (i.e. whether the SDCs are saturated at 8$\mu$m), (5) the average *Herschel* column density and (6) the peak $\tau_{8\mu m}$ recalculated using the measured $I_{\text{fore}}/I_{\text{MIR}}$ fraction.
To investigate whether there are more SDCs in bright regions, we compare the distribution of Herschel-detected SDCs with the 8\textmu m radiation field, \(I_{\text{MIR}}\), in Figure 3.2. We can see that whilst there are slightly more SDCs in regions with very bright 8\textmu m emission, such as the two bright regions at \(l \sim 351^\circ\) and \(353^\circ\) (the star formation regions NGC6334 and NGC6357) and the Galactic centre, there is not a dramatic decrease in the number of SDCs in regions with less 8\textmu m emission. We are also able to detect IRDCs even in regions with fairly low background emission, with the number of SDCs extracted decreasing only when \(I_{\text{MIR}}\) approaches 0. This implies that IRDCs are not only associated with active star forming regions, but can also be found in more quiescent regions. We wish to note that there are completeness limitations in dark regions as we will not detect SDCs if there is no background emission and there may be confusion in regions with a high number density of SDCs as SDCs may overlap along the line of sight.

### 3.2.1 Latitude Distribution

We can see from Figure 3.2 that the SDCs tend to be concentrated towards the Galactic plane (i.e. \(b = 0^\circ\)), where the ISM is densest. Figure 3.3 shows histograms of the latitudes of the Herschel-detected SDCs (shaded) for several sections of the Galactic plane (\(|l| < 1^\circ\), \(|l| < 10^\circ\) and \(|l| < 65^\circ\)). As it is possible that any SDC with a radius of less than 20" cannot be detected in Herschel column density, we also include these small SDCs in additional histograms (unshaded). These histograms all peak near \(b \sim 0^\circ\), suggesting that IRDCs form preferentially within the disc of the galaxy, however the histogram peaks are all shifted slightly towards negative latitudes. For \(|l| < 65^\circ\), gaussians have been fitted to both histograms, both with an FWHM of \(\sim 59^\prime\) and centred at \(b \sim -5^\prime\). Gaussians fitted to the Herschel-detected SDCs only in the regions \(|l| < 10^\circ\) and \(|l| < 1^\circ\) have very similar parameters. This slight asymmetry originates from the Sun’s location slightly above the Galactic plane which causes the near side of the
3: SDC ANALYSIS

Figure 3.2: Top - The distribution of the Herschel-detected SDCs (green stars) and SDCs with sizes of 20" or less (blue dots) within the central 20° of the galaxy. Bottom - The mid-infrared background at 8µm (bottom) in the region |l| < 10°, |b| < 1°. The latter was found by smoothing the data to 5′ and reducing the pixel size to 2′×2′. The colour bar shows the colour scale in MJy/Sr. Note that for clarity the both panels are stretched in latitude.


The histograms drawn for the longitude range |l| < 1° show an interesting peak at around b ~ −0.5°. This secondary peak is apparent whether we include the small SDCs or not, careful examination of the Spitzer 8µm images shows that there is a possible
Figure 3.3: The latitude distribution of the *Herschel*-detected Spitzer Dark Clouds (shaded) (a) in region $|l| < 1^\circ$, (b) in region $|l| < 10^\circ$ and (c) in region $|l| < 65^\circ$. The unshaded histograms include those undetected SDCs with an equivalent radius of less than 20″. The curve fitted to the unshaded histogram (excluding the peak around $b = -0.5^\circ$) in (a) is the sum of two gaussians with a narrow component of FWHM = 19′ and a wide component of FWHM = 55′, with their peaks at $b = -1.2'$ and $b = -8.8'$ respectively. The broader component of these fits is shown as a dashed curve and the sum of the two components as the upper solid curve. The best fitting Gaussian to only the *Herschel* detected clouds greater than 20″ in size is also shown (lower solid curve on each panel). It has a width of 61′ and a peak at $b = -6'$. Similar fits (also excluding the peak around $b = -0.5^\circ$) are shown in (b). In this case the narrow component has a width of 18′ and a peak at $b = -1.6'$ while the broad component has a width of 81′, peaking at $b = +2.3'$. For both sets of clouds shown in (c) only a single gaussian component is fitted.

filament lying at this latitude, below the Galactic centre and parallel to the Galactic plane. A large number of SDCs are extracted from this structure, all at roughly the same latitude, causing a peak in the histograms. Such structures are discussed further in Chapters 4 and 5. Another interesting feature in the $|l| < 1^\circ$ histogram including the small SDCs is the narrowing of the peak at $b \sim 0^\circ$. This narrowing towards the Galactic centre is not apparent in the *Herschel*-detected SDCs only nor when considering the entire longitude range, $|l| < 65^\circ$. Although ~50% of these smaller sources are likely to be false detections, as the narrow peak is four times higher than the peak of the *Herschel*-detected SDCs, uniformly removing 50% of the sample of small SDCs would not affect the result. It may be that the SDCs around $b = 0^\circ$ are more likely to
be false as the background is higher between $-0.3 < b < 0.2$. If around 75% of the small SDCs in this region are false (and 50% elsewhere) then the peak would reduce to the wider component indicated by the dashed line in Figure 3.3(a). Figure 2.15 shows that the this detection rate may occur when $I_{\text{MIR}} > 200\text{MJy/Sr}$, which is the case for the region $|b| < 0.1^\circ$. However the narrow peak extends beyond this latitude range, indicating that this narrow peak is unlikely to be entirely due to false, small SDCs.

The histogram including the smaller SDCs is thus fitted with two gaussians (ignoring the peak at $b \sim -0.5^\circ$), one to the wider component (FWHM = 55′ centred at $b = -8.8′$) and one to the narrower component (FWHM = 19′ centred at $b = -1.2′$). We would expect SDCs associated with the Galactic centre to appear smaller due to their greater distance from the Sun and to be located at $b \sim 0^\circ$ no matter what the angle we view the Galactic disc. As the narrower peak is closer to $b = 0^\circ$ and it is only apparent in the smaller SDCs, this indicates that the narrow component represents the SDCs that are associated with the Galactic centre whilst the wide component represents the SDCs along the line of sight, as suggested by Yusef-Zadeh et al. (2009).

The $|l| < 10^\circ$ histograms show similar features to the $|l| < 1^\circ$ histograms, with a secondary peak at $b \sim 0.5^\circ$ and a narrowing of the peak in the histogram including the smaller SDCs. There is another, smaller peak at $b \sim +0.7^\circ$ that most likely represents another structure, possibly a filament, in this region. As with $|l| < 1^\circ$, two gaussians are fitted to the unshaded histogram with a broad component (FWHM = 81′ centred at $b = 2.3′$) and a narrow component (FWHM = 18′ centred at $b = -1.6′$). Although the broad component peaks at a positive latitude, it is apparent from the histograms that this is due to the influence of the additional peak at $b \sim +0.7^\circ$.

Yusef-Zadeh et al. (2009) performed a similar analysis of the latitude distribution of 24µm point-like sources and candidate young stellar objects (YSOs) in the region $|l| < 1.3^\circ$, $|b| < 1.5^\circ$. They also fitted these latitude distributions with two gaussians, a
broad and a narrow component, in the same manner as shown in Figure 3.3. The widths of the narrow components were FWHM = 15′ for the 24µm sources and FWHM = 5.5′ for the YSO candidates. As the width of the narrow component found in the SDCs in the region |l| < 1° (19′) most closely matches the 24µm point-like sources, it is possible that some of these 24µm sources are associated with star formation in the SDCs towards the Galactic centre. The secondary peak associated with a filamentary structure at $b \sim 0.5°$ is not seen in the latitude distribution of either the 24µm sources or YSOs. This is either because the peak is too small to be seen in the much larger sample of 24µm sources or may be because the SDCs in the filament are at an earlier evolutionary stage than the SDCs towards the Galactic centre. Further analysis of the 24µm point-like sources towards the SDCs would be required to resolve this.

3.3 Properties of the SDCs Towards the Galactic Centre

The latitude distribution of the SDCs suggests that it is likely that some of the SDCs observed towards the Galactic centre are indeed associated with the Galactic centre and not merely lying along the line of sight. Hence we can examine the properties of these SDCs to see if the extreme conditions present in the Galactic centre affect the properties of the IRDCs. We define the Galactic centre by drawing a box around the brightest emission seen in Figure 3.2, giving the coordinates $-0.7° < l < 0.6°$, $-0.3° < b < 0.2°$. The SDCs within this box will contain a population of SDCs that are associated with the Galactic centre as well as those SDCs that lie along the line of sight.

In Figure 3.4 we compare the peak 8µm opacity, average column density and median colour temperature of the SDCs in several populations. The first three histograms compare the Herschel-detected SDCs in the box around the Galactic centre with those outside this box, the second row of histograms are the same as the first but include the
SDCs with an equivalent radius of less than 20''. Whilst the Galactic centre represents the most extreme environment in the galaxy, other regions such as the active star forming regions NGC6357 and NGC6334 in Figure 3.2 may also have higher temperatures and be more turbulent due to feedback from young stars. Such regions tend to have high $8\mu$m emission as the UV radiation from the young stars illuminates the PAHs, which emit radiation at $8\mu$m. For this reason we also compare the Herschel-detected SDCs in bright regions, defined as those regions where $I_{\text{MIR}} > 80\text{MJy/Sr}$, with those in regions of lower background in the third row of Figure 3.4. In order to ensure that any apparent trend is statistically significant we use two-sided Kolmogorov-Smirnov (KS) tests to find the probability that the two histograms originate from a single data set. In all cases in Figure 3.4 the probability that the two histograms are drawn from the population is less than $10^{-5}$, showing that the differences are indeed statistically significant. Hence the probability that the SDCs towards the Galactic centre are drawn from the same population as the SDCs in the rest of the Galactic plane is less than $10^{-5}$, indicating the apparent increase in opacity and column density is statistically significant.

These histograms show that SDCs towards the Galactic centre tend to have a greater $8\mu$m opacity and a higher average column density than those in other regions. The median colour temperature of the Galactic centre SDCs is also slightly higher than we find elsewhere, indicating that the apparent increase in Herschel column density is not caused by lower temperatures. This is consistent with molecular line observations which show that molecular clouds in the centre of the galaxy tend to be denser than those in other regions (see e.g. Bally et al. (1988); Oka et al. (1998); Tsuboi et al. (1999); Oka et al. (2001)). Note that in all three comparisons, the peak opacity distributions show an increase at $\tau_{8\mu m} \sim 6$; these SDCs are saturated and hence their peak opacity is a lower limit (see Section 2.2.3). The SDCs in regions that are bright at $8\mu$m show similar properties to those in the Galactic centre. These results indicate that the SDCs are indeed affected by their environment, whether they are located near the...
3.3: PROPERTIES OF THE SDCS TOWARDS THE GALACTIC CENTRE

Figure 3.4: Histograms comparing the peak 8µm opacity, average Herschel column density and median Herschel colour temperature in different populations of SDCs. (a), (b) and (c) compare the Herschel-detected SDCs with $R_{\text{core}} > 20''$ towards the Galactic centre with all other Herschel-detected SDCs with $R_{\text{core}} > 20''$. (d), (e) and (f) compare the same populations as in (a), (b) and (c) but with the SDCs with $R_{\text{core}} < 20''$ included, whether Herschel-detected or not. (g), (h) and (i) compare the Herschel-detected SDCs with $R_{\text{core}} > 20''$ in regions of high $I_{\text{MIR}}$ ($>80\text{MJy/sr}$) and low $I_{\text{MIR}}$ ($<80\text{MJy/sr}$). In all cases the probability the two group are part of the same population is less than $\sim 10^{-5}$. The flattening and up-turn seen in the peak 8µm opacity distributions is due to saturation [Peretto & Fuller (2009)].
centre of the galaxy or in other dynamic regions. We speculate that the higher densities and warmer temperatures observed may be due to an increase in turbulence or additional thermal support in the molecular clouds, however we cannot currently state the link between the conditions in such regions and the resulting properties of the SDCs.

There are some selection effects to be aware of in Figure 3.4. The distance to the Galactic centre means we will have a greater number of foreground sources than towards other bright regions. In addition, those SDCs that are associated with the Galactic centre must be, on average, larger than foreground SDCs in order to be resolved. Larger SDCs will have a greater mass and this could mean they have a greater density, meaning we are more likely to detect the densest SDCs towards the Galactic centre. However this will not be the case for other bright regions which are likely to have the same distance distribution as in less bright regions.

3.3.1 Is G0.253+0.016 unique?

One particularly extreme IRDC located near the Galactic centre (G0.253+0.016 or SDC0.341+0.095) is thought to be a progenitor of an Arches-like massive cluster, despite the absence of current star formation [Longmore et al. (2011)]. This SDC has a dust mass of $\sim 10^5 M_\odot$, an average density of $8 \times 10^4 \text{cm}^{-3}$ and is saturated at 8$\mu$m. It is part of the elliptical ring identified by [Molinari et al. (2011)], placing it at a distance of 60-100pc from the Galactic centre. Now that we have a complete sample of the IRDCs towards the Galactic centre, we can determine if there are other, similar IRDCs that may be future sites of massive star clusters.

As this SDC is highly saturated, the peak opacity will be underestimated, however this SDC has the highest average opacity in the SDC catalogue ($\tau_{av} = 3.7$). There are only 7 SDCs with $\tau_{av} > 2$, four of which lie within towards the Galactic centre (as defined by the region of high $I_{\text{MIR}}$) and two of which are part of the elliptical ring feature.
3.4: SUMMARY

We also find that G0.253+0.016 has the second highest average column density in the SDC catalogue, with the highest belonging to the other SDC in the elliptical ring. Hence although IRDCs with such high densities as observed in G0.253+0.016 are rare, others are present throughout the galaxy. The appearance of two of these IRDCs in the Galactic centre ring indicates that this represents a unique environment that will influence future star formation.

3.4 Summary

In this chapter we have used the SDC catalogue to show that IRDCs are a common feature in the Galactic plane and have been identified everywhere there is enough background emission for them to absorb. There does not appear to be a significant increase in the number of objects found in regions with high 8$\mu$m background emission, suggesting that the formation of IRDCs does not rely on a dynamic environment. The latitude distribution of the SDCs show that the SDCs tend to lie along the Galactic plane, with a peak in the distribution near $b = 0^\circ$. There is a slight asymmetry to the latitude distribution that suggests that the Sun does not lie directly within the Galactic plane, but is elevated slightly above the disc. The shape of the latitude distributions for the SDCs with $R_{eq} < 20''$ narrows when considering only those SDCs towards the centre of the galaxy. This suggests that there is indeed a population of SDCs that are associated with the Galactic centre, as well as a population that lies along the line of sight.

We have characterised the SDCs within the catalogue by finding the properties listed in Tables [3.1] and [3.2]. This has allowed us to compare the properties of SDCs towards the Galactic centre with SDCs in other regions. We find that such SDCs tend to have a higher column density and a slightly higher temperature that SDCs in other regions. This trend is continued in all regions where $I_{\text{MIR}} > 80\text{MJy/Sr}$, which tend to be active star forming regions. This implies that IRDCs are affected by their environments and
3: SDC ANALYSIS

may have further implications for future star formation in these SDCs.
Infrared Dark Filaments

Filaments have long been associated with star formation (e.g. Elmegreen & Lada (1977); Schneider & Elmegreen (1979); Bally et al. (1987)). However recent observations with Herschel have highlighted the importance of filaments in star formation, prompting a renewed interest in filamentary structures.

One of the most striking results of the HiGAL survey was the prominence of filamentary structures in the interstellar medium. Molinari et al. (2010a) demonstrated the proliferation of filaments by taking the second derivative of the $l = 59^\circ$ HiGAL tile (see Figure 4.1). Molinari et al. also used this data to compile a catalogue of compact sources seen at 250$\mu$m; these compact sources represent cores that are likely sites of star formation. We can see in Figure 4.1 that these cores are found almost exclusively within the filaments. Filaments are clearly an important part of the star formation process and are a common feature in the Galactic plane.

Similar networks of filaments have been observed in several regions of star-formation. For example filament networks have been identified in IC5146 (Arzoumanian et al. 2011), Vela C (Hill et al. 2011) and the Pipe nebula (Peretto et al. 2012). Men'shchikov et al. (2010) associated starless cores with filament networks in Aquila and Polaris. Such observations support the idea that the star formation process is initiated when
diffuse molecular clouds collapse into networks of filaments.

In addition to these networks within molecular clouds, there are a few examples of filaments that exist in isolation. The Nessie nebula (Jackson et al. 2010) is one such filament, with a length of 80pc and a width of 0.5pc, that appears in absorption at 8µm. This infrared dark filament lies along the Galactic plane and does not belong to a network of filaments. The Snake nebula (G11.11-0.12, Carey et al. (1998)), a shorter example at around 30pc in length, is also isolated from other structures. These filaments are not located within GMCs and so must be formed in a different manner. They are, however, no less important in star formation; both the Nessie and Snake nebulae contain star-forming cores. These two examples do not appear in the SDC catalogue as single SDCs as parts of the filaments do not have a high enough opacity to be detected. However, the densest parts of these filaments are detected as SDCs, meaning that these filaments contain several SDCs spread along their length. Few examples of such filaments are known, however with a catalogue of IRDCs across the Galactic plane, it is now possible to search for such filaments by looking for long strings of SDCs.

4.1 Minimum Spanning Trees

One way to identify connections between objects is to use minimum spanning trees (MSTs). Minimum spanning trees were first used in an astrophysical context to find interGalactic filaments by examining galaxy distributions (Barrow et al. 1985). They have been applied to a wide variety of data sets including cosmic ray distributions (Harari et al. 2006), molecular clouds (Lahaise & Bhavsar 1994), the Millennium simulation (Colberg 2007), stellar clusters (Schmeja et al. 2009) and infrared sources (Billot et al. 2011). In this chapter, we apply an MST algorithm to the SDC catalogue to find large-scale filaments consisting of strings of SDCs.
4.1: MINIMUM SPANNING TREES

Figure 4.1: The second derivative image of the \( l = 59^\circ \) HiGAL tile showing filaments in the ISM (taken from Molinari et al. (2010a)). The blue dots are compact 250\( \mu \)m sources, highlighting the importance of filaments in star formation.

4.1.1 MST Algorithms

The SDC catalogue can be considered to be a series of points spread across the Galactic plane. To find filamentary structures in the SDCs, we must connect those points which are spatially related. Although in reality the SDCs seen in projection close to one another on the sky may be at different distances, it is still possible to find structure by connecting those SDCs that are nearby when projected into two dimensions.

Considering the shortest connections between points has long been considered in graph theory. A graph is a series of points, or vertices, connected by lines, or edges, with a known weight. A subset of these edges is known as a tree as shown in Figure 4.2. The travelling salesman problem considers a similar situation in which the minimum distance a salesman must travel to visit several houses is calculated. The solution to this problem is to use a minimum spanning tree (MST). MSTs are graphs that connect all the vertices in a graph such that the total weight of the edges is minimised. As such there can be no closed loops within an MST. There are two commonly used algorithms...
that construct MSTs: Kruskal’s algorithm (Kruskal 1956) and Prim’s algorithm (Prim 1957). Kruskal’s algorithm can be described as:

- Find the edge with the smallest weight and add it to the tree. If more than one edge has the smallest weight, choose one arbitrarily.
- From the remaining edges, choose the edge with smallest weight.
- Provided a loop is not created, add this edge to the tree.
- Repeat these last two steps until all vertices have been added to the tree.

Kruskal’s algorithm works well if all the edges have unique weights, however if there is more than one edge with the same weight one of these edges must be chosen arbitrarily. As we cannot create loops, the choice of edge can affect the final MST constructed. Prim’s algorithm overcomes this problem by considering the vertices rather than edges:

- Arbitrarily choose one vertex and add it to the tree.
- Choose the shortest edge connected to the vertex.
- Add this edge and its associated vertex to the tree.
- Choose the shortest edge connected to any vertex in the tree.
- Provided no loops are created add this edge and its associated vertex to the tree.
- Repeat these last two steps until all vertices have been added to the tree.

Although one vertex must be chosen as a starting point, as all vertices must ultimately be added to the tree the choice of initial vertex does not affect the resulting MST constructed. For this reason we choose to use Prim’s algorithm to find filamentary structures in the SDC catalogue.
4.1: MINIMUM SPANNING TREES

4.1.2 Finding MSTs in the SDC Catalogue

Prim’s algorithm can be used with any graph with well defined edges and vertices and so can be applied to the SDC catalogue using the position of the peak opacity of the SDCs as vertices and the distances between the SDCs as the weight for each edge. However IRDCs are not point-like sources; they are extended structures and can have a highly filamentary shape. If two filamentary SDCs lie end-to-end, the distance between their opacity peaks could be too large to be included in the MST even though the ends of the SDCs are close together. This means a filament that is made of several filamentary SDCs strung out along its length could be missed. For this reason we consider an SDC as two vertices, one at each end of its major axis, connected by an edge. A small adjustment to Prim’s algorithm must be made to account for this, when one vertex of an SDC is added, the other must also be added. We can now apply this algorithm to the SDC catalogue, choosing the SDC with the lowest Galactic longitude as an initial vertex, to obtain an MST connecting all the SDCs.

Figure 4.2: (a) An example graph with weighted edges and (b) the minimum spanning tree constructed using Prim’s algorithm.
4: INFRARED DARK FILAMENTS

Whilst the SDCs in large-scale filamentary structures are connected by this MST, they are connected to every other SDC as well. Structure can be extracted from MSTs using a process called separating. Separating removes the edges from the MST that have an edge weight greater than a threshold ($d_{\text{thresh}}$). This will allow sub-trees of SDCs that lie within a distance $d_{\text{thresh}}$ from each other to be extracted from the main MST as demonstrated in Figure 4.3(c).

The sub-trees extracted may contain large-scale filaments, however they are also likely to contain SDCs that are not spatially related to these structures and are merely projected onto the same area of the sky. As we expect filaments to be long strings of SDCs, we can minimise the number of unrelated SDCs in the sub-trees by ‘pruning’ the branches from the sub-tree. As can be seen from Figure 4.3(c), the large sub-tree has several branches coming from the main structure. SDCs in branches only one or two edges long are most likely unrelated to the filaments, so we remove any branch that has less than three edges to reveal the main structure (see Figure 4.3(d)).

Finally, some of the sub-trees remaining are still likely to be simply projected onto the same area of sky. However, the more SDCs there are in a sub-tree, the more likely that sub-tree represents a genuine structure. By examining by eye all the sub-trees in the region $l = 330^\circ$ to $l = 340^\circ$, we find that true structures tend to contain at least 10 edges (or 11 SDCs) and so we extract only these sub-trees from the MST. Whilst this means that some smaller structures will be missed in this way, too many of the smaller sub-trees seem to be chance projections and without information on the distances to SDCs it is almost impossible to say if any of the smaller structures are indeed spatially related.

To test this procedure and ensure that structure can be extracted from a background distribution of points, we superimposed a known structure onto a random distribution.
4.1: MINIMUM SPANNING TREES

Figure 4.3: A test filamentary structure (b) is superimposed onto the random distribution (a). The minimum spanning tree of these vertices is found (c), separated with $d_{\text{thresh}} = 5$ (d), pruned (e) and then any structures with more than 10 edges extracted (f).

Clare Lenfestey
of vertices and applied the algorithm described above (see Figure 4.3). We can see from
the figure that the test structure is indeed extracted from the background distribution
and its shape is well-defined. We also note that several other vertices lying near this
test structure are part of the final sub-tree. This is unavoidable and, in the case of any
filamentary structures identified in this way, means that we will have some unrelated
SDCs in the final sub-trees.

4.1.3 Choosing $d_{\text{thresh}}$

The sub-trees extracted from the MST depend greatly on the maximum edge weight,$d_{\text{thresh}}$. However as any filaments are superimposed on a background distribution of
SDCs, the distance at which two SDCs are considered to be significantly close will
depend on the typical distance between the SDCs in that part of the sky. In an area
with few SDCs, if several SDCs lie in the same vicinity they could be considered to
be related, however in an area with a high number density of SDCs, they must be very
close together to be considered part of a coherent structure. Hence we do not set the
parameter $d_{\text{thresh}}$ as a simple constant, but we let it depend on the typical separation of
the surrounding SDCs.

The typical separation between the SDCs was characterised at the position of each
SDC by taking all the SDCs within 20′ and finding the mean area per SDC, $A_{\text{cloud}}$. The
square root of $A_{\text{cloud}}$ then gives the typical separation of the SDCs in that area. $d_{\text{thresh}}$
was then defined as

$$d_{\text{thresh}} = \begin{cases} \ a \sqrt{A_{\text{cloud}}} & \text{if } a \sqrt{A_{\text{cloud}}} < 5' \\ 5' & \text{otherwise} \end{cases} \quad (4.1)$$

where $a$ is a constant. The imposition of a maximum $d_{\text{thresh}}$ ($d_{\text{max}}$) ensures that $d_{\text{thresh}}$
does not become too large in regions with few SDCs. By varying $a$ and the maximum
$d_{\text{max}}$ we found that $a = 0.65$ and $d_{\text{max}} = 5'$ ensured that structure could be defined in
Figure 4.4: Figures showing the effect of varying the MST parameters. In (a), (b) and (c) the factor $a$ is varied from 0.45 to 0.75, whilst $d_{\text{max}}$ is kept constant, in a region where we identify 2 filamentary candidates. Note that in (c) the two structures are not resolved whereas in (a) we miss a possible filament. (d) and (e) show the effect of increasing $d_{\text{max}}$ to 6′ in a region where we extract 1 filamentary candidate. The additional structures in (c) and (e) do not appear to be genuine structures, merely randomly connected SDCs that lie near each other on the sky.

regions with a high SDC number density whilst still allowing known filaments (e.g. Nessie, Snake, NGC6334) to be extracted. Figure 4.4 shows the effect of varying $a$ and $d_{\text{max}}$ on the sub-trees extracted.

The computing time of taking a single MST considering 8113 SDCs, each with two vertices, and edges connecting each vertex to every other vertex is considerable. Hence we applied the algorithm to 10° blocks of the Galactic plane at a time. To ensure that no structures were missed or truncated at the edge of a block, each block overlapped its
4: INFRARED DARK FILAMENTS

Figure 4.5: The sub-trees extracted from the region $l = 334^\circ - 344^\circ$, $|b| < 1^\circ$. The long structure at $l \sim 338^\circ - 339^\circ$ is the Nessie nebula.

neighbours by $2^\circ$. As Nessie has a major axis of just over $1^\circ$, this should be sufficient to ensure all structures can be extracted in their entirety. If a sub-tree appeared truncated by the edge of a block, it would have been possible to reapply the MST algorithm to this region, however in practice this was not necessary. Figure 4.5 shows the sub-trees identified in one such block of the Galactic plane.

In total 88 sub-trees were extracted from the SDC catalogue in this way. These sub-tree can now be investigated to determine the nature of the structure they represent.

4.2 Filamentary Candidates

The 88 sub-trees extracted from the MST may represent the large-scale filaments we seek, however they may also be SDCs that are associated but not part of a filament or SDCs that are not related and merely projected onto the same area of sky. Further investigation of these sub-trees and the SDCs contained within them is therefore required to verify the nature of the structures extracted from the SDC catalogue.

An initial analysis of the structures represented by the sub-trees can be made by simply examining $8\mu$m images of the area containing the sub-tree. These images were constructed by mosaicing the GLIMPSE and GLIMPSEII tiles together using the Montage software (http://montage.ipac.caltech.edu/). In order to ensure that the images
were large enough to contain the entire structure and its immediate surroundings, these images were given twice the dimensions of the sub-tree. In addition, column density maps were extracted for each image from the column density maps of each HiGAL tile constructed in Section 2.3.2. This allowed the material that is not dense enough to be seen in absorption at 8µm to be observed, providing greater confidence that the SDCs are indeed related. These images were then examined by eye to determine whether they contained a large-scale infrared dark filament, other structures or nothing at all. Further observations would be required to confirm these SDCs lie at the same distance from the Sun and are indeed spatially related.

The complete list of structures extracted from the SDC catalogue are listed in Table 4.2. The names given to these structures are ‘F’ followed by the longitude of the opacity peak of the SDC at the start of the sub-tree (i.e. with the minimum longitude) followed by the longitude of the opacity peak of the SDC at the end of the sub-tree. As the minimum longitude is unique, we shorten this to Flll.lll for convenience, using the minimum longitude only.

4.2.1 Filament Candidates

When the 8µm images and column density maps were examined, several different structures were observed. None of the sub-trees appeared to consist of unrelated SDCs, although further observations would be needed to confirm this. We put these structures into four categories: Complex networks, hub-filaments, bubble-like filaments and linear filaments.

The most common structure seen were the complex networks (see Figure 4.5(c)). These structures appear to be form parts of networks of smaller filaments, similar to those seen in molecular clouds (e.g. Vela C, Aquila, Pipe). They tend to be found in regions with bright 8µm emission and are likely to be part of a more complex system.
While these networks are interesting structures, we restrict ourselves to more simple structures for further study.

Eight of the filamentary candidates are categorised as bubble-like filaments (see Figure 4.5(a)). Such circular or bow-shaped features could be formed at the outer edge of an expanding shell. Supernovae or strong winds from stars or stellar clusters may sweep up material into a shocked layer. Bubbles seen in emission at 8µm are common features in the Galactic plane: Churchwell et al. (2006, 2007) have found ~600 in the GLIMPSE region. In order to find bubbles as IRDCs, the swept up material must become dense and cold enough to absorb at 8µm. Such IRDCs have been observed either along the edge of the bubbles or radiating away from them (Anderson et al. 2012; Ntormousi et al. 2011). Of the 8 bubble-like filaments, we could only identify the central object in one case. This structure appears in a bow-shape around an expanding HII region known as Gum 48d. This HII region is illuminated by a binary system of 2 supergiants, both thought to have been O-type stars (Karr et al. 2009). The MST sub-tree traces the SDCs at the outer edge of this 8µm emission.

Seven of the candidate filaments are categorised as hub-filaments. Hub-filaments consist of a large central ‘hub’ with filaments radiating away like the spokes of a wheel (Vázquez-Semadeni et al. 2007; Myers 2009). Several mechanisms have been suggested that could form hub-filaments. Colliding flows could produce a hub-filament at their intersection (Jappsen et al. 2005). Vázquez-Semadeni et al. (2007) model two colliding cylinders of gas and produce a hub-filament in the plane where the two meet. Myers (2009) take this further and suggest that hub-filaments are formed through layer fragmentation when parsec-scale flows collide. Simulations of magnetised clouds with dissipating turbulence have also produced hub-filament features as the cloud condenses along the field lines (Nakamura & Li 2008).

In the structures identified here, the central hub is either a bright emission feature...
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at 8µm or a dark absorption feature. The example shown in Figure 4.5(b) has a dark hub and two long, dark filaments radiating away. The MST sub-tree detects these two long filaments, although other shorter filaments can be seen radiating away from the dark central hub. This is a particularly interesting structure as it is part of the star formation region NGC6334 which has a well-known filament running through it. This hub-filament lies at one end of this filament. The rest of the filament is detected separately.

The final category is the linear filaments. These are simple, long and relatively isolated structures similar to the Nessie nebula. Twenty-two of the filament candidates are identified as linear, including NGC6334, Nessie and Snake nebulae. An example of a linear nebula is shown in Figure 4.5(d). The full list of filaments and the category they have been placed in is given in Table 4.2.

4.3 Filament Properties

With a sample of 88 filaments, it is now possible to investigate the properties of these filaments. One of the defining features of filaments is their large aspect ratio (the ratio between their major and minor axes). To find the aspect ratio, we must first find the major and minor axes of the filaments. In addition we find the position angle of the filaments, defined as the angle between the major axis and the Galactic plane.

As with the SDCs in Section 3.1 we define the major and minor axes, ΔX and ΔY, using the moment of inertia. For each structure, we first find the centroid position by taking the mean longitude and latitude (\( \bar{l}, \bar{b} \)) of the SDCs. The moment of inertia matrix is then defined as:

\[
I_{xx} = \sum_{i=1}^{N} m_i (b_i - \bar{b})^2
\]  (4.2)

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(a)  
(b)  
(c)  
(d)  
(e)  
(f)  

Clouds and Filaments
Figure 4.5: Examples of the different morphologies represented by the filamentary candidates shown at 8µm (left) and their minimum spanning trees (right). (a) and (b) show a structure with a bubble morphology (F20.034), (c) and (d) show the hub-filament associated with NGC6334 (F350.286). This has a dark hub and two long, thin filaments going from top left to bottom right. The MST starts tracing one filament then switches to the other half-way down. This is as the top part of the fainter filament is has a bright feature that interrupts it and pruning removes the rest of the darker filament. (e) and (f) show a more complex region from which two filamentary structures are identified (F326.618 and F326.750) and (g) and (h) show a linear filament (F357.588).

\[ I_{yy} = \sum_{i=1}^{N} m_i (l_i - \bar{l})^2 \]  
(4.3)

\[ I_{xy} = \sum_{i=1}^{N} m_i (b_i - \bar{b})(l_i - \bar{l}) = I_{yx} \]  
(4.4)

where \( l_i \) and \( b_i \) are the positions of the opacity peaks of the SDCs and \( m_i \) is the mass.
of the SDC. As we do not wish to weight any SDC as more important than the others, we set $m = 1$ for all SDCs. The directions of the major and minor axes are then found by diagonalising this matrix and finding the eigenvectors. The position angle, $\alpha$, of the major axis w.r.t. the Galactic plane can then be determined by taking the angle between the line $b = 0$ and the eigenvector of the major axis. We set $-90^\circ < \alpha < 90^\circ$ with positive angles in the direction of positive latitude (see Figure 4.6).

The distance of each SDC from the centroid of the filament along the direction of the eigenvector is given by $\sigma_x$. We take the length of the major axis of the filament to be twice the maximum value of $\sigma_x$, where

$$\sigma_x^2 = [(l_i \cos \alpha - b_i \sin \alpha) - (\bar{l} \cos \alpha - \bar{b} \sin \alpha)]^2$$

Similarly the length of the minor axis is given by the twice the maximum distance of an SDC from the centroid in the direction of the eigenvector describing the minor axis, $\sigma_y$, where

\[ \sigma_y^2 = \]
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\[ \sigma_y^2 = [(l_i \sin \alpha + b_i \cos \alpha) - (\bar{l} \sin \alpha - \bar{b} \cos \alpha)]^2 \]  

(4.6)

The aspect ratio is then defined as \( \Delta X/\Delta Y \). The lengths of the major and minor axes, position angles and aspect ratios for each filament are given in Table 4.2. Note that these are first estimates of the major and minor axes, aspect ratios and position angles of the sub-trees. These sub-trees will contain unrelated SDCs and as such are not always representative of the actual filament. This will not greatly affect the position angle as the general direction of the filament is well estimated by the sub-trees, however the minor axis tends to be overestimated and hence the aspect ratio is underestimated. It is relatively simple to identify which SDCs belong to the linear filaments, so in Table 4.2 the major and minor axis, position angles and aspect ratios have been found using these SDCs only, not the whole sub-tree.

4.3.1 Alignment with Galactic Plane

One of the features of the sub-trees extracted from the SDC catalogue is that they appear to lie preferentially along the Galactic plane (see Figure 4.5). A histogram of the position angles of the filaments shows that the filaments do indeed tend to lie along the Galactic plane. This trend is particularly apparent when we consider only the linear filaments (see Figure 4.7).

The MST algorithm does not show any preference in direction and so this trend is not a result of the detection method. We might naively expect that as we only observe 2° of latitude, we are less likely to detect filaments parallel to the galactic plane as they leave the survey area. However even if we are not able to detect an entire filament, provided 11 SDCs are within the survey area, we will detect parts of these filaments. As such, the bias towards the Galactic plane is not due to the limits of the survey area. We speculate that this bias towards hints at the importance of the passage of the spi-
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Figure 4.7: Histogram of the position angles of the filaments (unshaded), taking the modulus of the position angles to more easily see the trend. Also shown is the histogram for linear filaments only (shaded).

Spiral arms through the Galactic plane. As the dust and gas in the leading edge of the spiral arms is condensed, filaments may form preferentially parallel to the spiral arms. It is also possible that the magnetic field in the Galactic plane, which acts parallel to the Galactic plane, restricts the direction of the filaments along the magnetic field lines.

Numerical simulations by Dobbs et al. (2006) show that spiral shocks moving through the Galactic plane can form molecular clouds (see Figure 4.8). Although such simulations do not yet explain how filaments with such high aspect ratios form, they do show that the spiral arms of the galaxy can be traced by long molecular clouds within the Galactic plane. Goodman et al. (2013) have shown that Nessie could be extended to a length of up to 800pc, 10 times the length observed by Jackson et al. (2010). Goodman et al. suggest that such long, highly filamentary ‘bones’ of IRDCs can be used to trace the spiral arms in the Milky Way. While at present the formation process of such
narrow filaments is unclear, their alignment with the Galactic plane implies that their formation relies on such spiral shocks.

### 4.3.2 Filament Distances

The distance to the SDCs in a filament and whether apparently related SDC are in fact close in space (rather than just in projection) can be estimated from observations of the velocity and velocity dispersion of the dense gas in the clouds. A sample of SDCs in apparent filaments was observed with the ATNF Mopra telescope. The system was configured to observe several spectral lines. Here we will focus on just the velocity information obtained from J=1-0 transition of HNC which traces the dense gas in these clouds (as demonstrated by Jackson et al. (2010)). At the frequency of this line Mopra has a beam size of 30” and the observations have a velocity resolution of 0.08 km/s. The spectral resolution of Mopra is 0.27MHz and the sensitivity is 0.05K.

Observations of three or four different cores within 6 different filaments have been made (see Table 4.1). All but one of these filaments (F329.090) show consistent ve-
loclities along the filament, confirming that these are indeed coherent structures. Four of the filaments have line peak velocities that are spread over less than $3\text{km}\cdot\text{s}^{-1}$ and F351.459 has velocities spread over $7\text{km}\cdot\text{s}^{-1}$. F329.090 is an unusual structure, containing cores with a velocity range of $28.4\text{km}\cdot\text{s}^{-1}$, that appears to change direction part way along the filament. This structure may be two filaments that overlap each other and not a single filament. Further observations would be required to resolve these velocity discrepancies.

The velocities of the HNC line can be used to estimate the kinematic distances of these filaments from the Sun using the procedure developed by Reid et al. (2009). This uses the rotation curve of the galaxy to estimate the distance an object would have from the Galactic centre using its velocity. This is then translated to a distance from the Sun using its Galactic longitude and latitude. In the inner galaxy this method gives two estimates of the distance; the near and far kinematic distances. The far kinematic distance lies on the other side of the Galactic plane, so to observe an SDC here we would have to observe it through a large amount of material in the Galactic disc and there would need to be a large amount of $8\mu\text{m}$ emission behind it from a source other than the disc. As it is unlikely that we would observe SDCs on the far side of the Galactic plane, we take the near kinematic distance. We find the distances at every position observed and take the mean to give the distance to the filaments. Due to the complicated nature of F329.090, we do not find a distance for this filament. In addition no distance can be found for F351.459 as it is too near the Galactic centre for the distance to be determined in this way. These distances are shown in Table 4.1.

In Section 5.4 we will use the velocity dispersions of the filaments to make predictions on the fragmentation of the filaments. We can find the velocity dispersion of the gas using the linewidth of these observations. The one-dimensional velocity dispersion (the velocity dispersion along the line of sight, $\sigma_{1D}$) is found by taking the FWHM of the HNC line and taking $\sigma_{1D} = \text{FWHM} / \sqrt{8 \ln 2}$. The three-dimensional velocity dis-
In this section, we have applied a MST algorithm to the SDC catalogue and obtained a list of 88 structures across the Galactic plane. These structures have been examined by eye at Clare Lenfestey and the effective sound speed, $c_{\text{eff}}$, can be determined from the HNC observations as

$$\sigma^2_{\text{HNC}} = c^2_{\text{HNC}} + \sigma^2_{\text{non-thermal}} \quad (4.7)$$

$$c^2_{\text{eff}} = c^2_{\text{H}_2} + \sigma^2_{\text{non-thermal}} \quad (4.8)$$

where $\sigma_{\text{HNC}}$ is the observed velocity dispersion, $c_{\text{HNC}}$ is the sound speed of HNC, $\sigma_{\text{non-thermal}}$ is the velocity dispersion due to turbulence and $c_{\text{H}_2}$ is the sound speed of H$_2$. This assumes that the turbulent velocities are the same for both HNC and H$_2$. As the sound speed of HNC at 20K is $89\text{ms}^{-1}$ which is much less than $\sigma_{\text{non-thermal}}$ so $\sigma_{1D} \approx \sigma_{\text{HNC}}$.

Some of the filaments are well-studied objects and so distances and velocity distributions can be found in the literature. These properties were found for the Nessie nebula (F338.098) (Jackson et al. 2010), the Snake nebula (F10.990) (Gómez et al. 2011) and NGC6334 (F351.459) (Russeil et al. 2010). Hence in total, we have estimates for the kinematic distances and velocity dispersions for 7 linear filaments in total.

### 4.4 Summary

We have applied an MST algorithm to the SDC catalogue and obtained a list of 88 structures across the Galactic plane. These structures have been examined by eye at Clare Lenfestey.
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<table>
<thead>
<tr>
<th>Filament</th>
<th>Velocity $\text{kms}^{-1}$</th>
<th>Linewidth $\text{kms}^{-1}$</th>
<th>Kinematic Distance (kpc)</th>
<th>$\sigma_{3D}$ (kms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F299.158</td>
<td>-38.3</td>
<td>1.37</td>
<td>4.1 ± 1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>F320.234</td>
<td>-32.4</td>
<td>2.8</td>
<td>2.3 ± 0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>F321.620</td>
<td>-32.4</td>
<td>3.2</td>
<td>2.3 ± 0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>F330.287</td>
<td>-41.2</td>
<td>2.1</td>
<td>2.8 ± 0.4</td>
<td>1.5</td>
</tr>
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<td>F338.098</td>
<td>-</td>
<td>-</td>
<td>3.1</td>
<td>1.8</td>
</tr>
<tr>
<td>F351.549</td>
<td>-</td>
<td>-</td>
<td>1.7 ± 0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>F10.990</td>
<td>-</td>
<td>-</td>
<td>3.6</td>
<td>3.0</td>
</tr>
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</table>

Table 4.1: The mean velocity and linewidths along the filaments observed with MOPRA and the kinematic distances and velocity dispersions found for these filaments. Also included are the three filaments for which kinematic distances and velocity dispersions could be found in the literature.

$8\mu m$ and in column density to identify the nature of their structure. We categorise 8 structures as bubble-like, 7 as hub-filaments, 22 as linear and the remaining 51 are considered to be part of more complex systems. We have found the lengths of the major and minor axes of these filaments and used these to calculate their aspect ratios. We also find the position angles of these filaments and find that many of the filaments lie parallel to the Galactic plane. This trend is particularly strong when considering only the linear filaments. This is likely to be a consequence of the spiral shocks moving through the Galactic disc.

Additional observations of the HNC line in several cores of 6 filaments have been made using MOPRA. These observations have shown that 5 of these filaments have consistent velocities throughout their length, confirming that they are indeed coherent
structures. In the one case where this is not true, the velocities are consistent with two overlapping filaments, although as only 3 velocities were measured in this filament we are unable to confirm that this is the case. These velocities and the widths of the HNC lines have been used to estimate the velocity dispersions of the gas within the filaments and to estimate the distance to these filaments. The literature has also yielded distances and velocity dispersions for 3 filaments, allowing distances and velocity dispersions to be estimated for a total 7 filaments. We can now use this information to investigate the fragmentation of these filaments into smaller cores that may ultimately form stars.
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<table>
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<tr>
<th>Filament</th>
<th>Major Axis (°)</th>
<th>Minor Axis (°)</th>
<th>Aspect Ratio</th>
<th>Position Angle (°)</th>
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### 4: INFRARED DARK FILAMENTS

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Table 4.2: Filamentary structures identified by the MST algorithm that appear to represent filamentary structures. This table shows the major and minor axes of the structures identified (columns 2 and 3), their aspect ratio (column 4) and their position angle relative to the Galactic plane (column 5). The category these filaments are placed in is shown in column 6.
4: INFRARED DARK FILAMENTS
5

Filament Fragmentation

Molinari et al. (2010a) show that star formation in the Galactic plane predominantly occurs within filamentary structures. However in order for a filament to form stars, it must first fragment into cluster-forming clumps and star-forming cores. Observations of the Nessie nebula (Jackson et al. 2010), Snake nebula (Henning et al. 2010) and G304.74+01.32 (Miettinen 2012) have shown that filaments are not simply cylinders of gas and dust, they tend to fragment into clumps that are spread along the length of the filament. These clumps form at regular intervals along the length of the filament, for example Jackson et al. (2010) found that the clumps in Nessie occur roughly every 4.5pc. To date, such analyses have been conducted on only a handful of filaments. We are now able to investigate the fragmentation of such filaments on a larger sample of objects.

5.1 Predictions of Fragmentation

The fragmentation of a cylindrical cloud into regularly spaced clumps is predicted by the ‘sausage’ instability. This instability was initially proposed by Chandrasekhar & Fermi (1953) for an infinite incompressible cylinder with an axial magnetic field and shows that oscillations travelling along the filament are only stable if the oscillations have wavelengths less than a critical value. If the oscillations are longer than this crit-
5: FILAMENT FRAGMENTATION

cal wavelength, matter will build up into clumps with a typical separation equal to this wavelength, forming clumps along the filament length. Furthermore they predict that there is a wavelength which is the most unstable, giving the fastest growing mode for these oscillations and a corresponding wavelength, $\lambda_{\text{max}} = 11R$ where $R$ is the radius of the filament. The filament will thus fragment into cores separated by a distance equal to $\lambda_{\text{max}}$.

This theory was refined by [Nagasawa (1987)] for an isothermal, thermally supported cylinder without a magnetic field. Nagasawa predicted that the fastest growing wavelength is given by $\lambda_{\text{max}} = 22.1H$ if $R >> H$, where

$$H = \frac{c_s}{\sqrt{4\pi G \rho_c}} \quad (5.1)$$

is the scale height, $R$ is the radius of the filament, $c_s$ is the sound speed and $\rho_c$ is the density at the centre of the filament. The scale height is the radius at which the cylinder is in hydrostatic equilibrium i.e. the radius at which the gravitational force on the gas particles is equal to the pressure from the particles within this radius. If $R << H$, $\lambda_{\text{max}}$ will reduce to $\lambda_{\text{max}} = 11R$ as in the case of an incompressible cylinder. Further refinements to the sausage instability have been made by e.g. [Nagasawa (1987); Nakamura et al. (1993); Fiege & Pudritz (2000)] to include various magnetic field configurations, however as we do not have any information about the magnetic field structure of the filaments, we choose not to consider these further.

The above analyses assume that the filaments are dominated by thermal pressure, however molecular clouds often have high velocity dispersions and may be dominated by turbulent pressure. [Fiege & Pudritz (2000)] show that if the filaments are dominated by turbulent motions, replacing the sound speed, $c_s$, with the velocity dispersion, $\sigma$, in Equation 5.1 gives a better estimate of the fastest growing wavelength, $\lambda_{\text{max}}$. [Jackson et al. (2010)] found that the spacing between the cores was best described when $\sigma$ was
used to find $\lambda_{\text{max}}$. However if both turbulent and thermal motions are important, $c_s$ can be replaced by the effective sound speed, $c_{\text{eff}}$ in Equation 5.1 to give the effective scale height, $H_{\text{eff}}$. Miettinen (2012) found that $\lambda_{\text{max}}^{\text{eff}} = 22.1H_{\text{eff}}$ most closely matched the observed spacing of the cores in G304.74+01.32. The effective sound speed is given by

$$c_{\text{eff}}^2 = c_s^2 + \sigma_{3D}^2$$  \hspace{1cm} (5.2)

where $\sigma_{3D}$ is the three-dimensional velocity dispersion.

With a larger sample of filaments, it is possible to test these predictions and use these results to investigate whether the filaments are likely to be dominated by thermal or turbulent pressure. First we need to determine whether the cores within the filaments are indeed regularly spaced.

### 5.2 Periodic Spacing of Clumps

To find out whether or not the 22 linear filaments have clumps that are equally spaced along the filament, we must first identify the clumps. We use the *Herschel* column density maps to find peaks in the column density which we identify as clumps. The clumps were found using the clump-finding algorithm used to find the peaks in the column density:dispersion maps 2.4 and fragments in the IRDCs (Section 3.1.2) designed by Peretto & Fuller (2009). As previously discussed, this clump finding algorithm relies on two parameters, $N_{\text{step}}$ and $N_{\text{thresh}}$. $N_{\text{thresh}}$ is the minimum contour below which we consider structure to be insignificant, we take $N_{\text{thresh}} = 0$ as we do not wish to exclude the smaller peaks at this stage. The size of the peaks extracted from the column density peaks depends strongly on $N_{\text{step}}$, as any peak must have a height of $N_{\text{step}}$ to be detected. For this reason $N_{\text{step}}$ was varied from $0.05 \times 10^{22}\text{cm}^{-2}$ up to $1 \times 10^{22}\text{cm}^{-2}$ for the densest filaments, increasing $N_{\text{step}}$ by $0.05 \times 10^{22}\text{cm}^{-2}$ each time. As when finding
fragments within the SDCs, each column density peak is described by the first contour at which the peak becomes unique. This allowed a mask of all the column density peaks in the filament and its surroundings to be identified.

As we are only interested in those column density peaks that lie along the filament itself, we need to discard the column density peaks in the surroundings. This was done by carefully comparing the column density maps with the peaks extracted and finding those peaks that belong to the filament by eye. Although some clumps are detected that seem to branch off from the main filament, we only choose those clumps that follow the main filament. The branches off the main structure may have different central densities and radii, so we would expect the fragmentation length to be different for the branches, so we do not include them in further analyses. The column density map of one filament with contours showing the clumps extracted in this way is shown in Figure 5.1.

Once the clumps within the filaments have been identified, we calculate the distance between the column density peak of one clump and the next along the filament. Histograms were then drawn of these nearest neighbour distances to see if there is a typical spacing between the clumps (see Figure 5.2).

When we examine the histograms of different $N_{\text{step}}$, we notice that the same spacing between the cores appears each time. This peak in the histograms does not move as $N_{\text{step}}$ is increased, although in some cases the initial peak becomes smaller and a second peak appears. This second peak represents the spacing of the densest clumps. There are several possible explanations for this observed second characteristic spacing. The clumps may themselves fragment into smaller clumps, resulting in a smaller spacing when we look at smaller column density peaks. When $N_{\text{step}}$ is increased, these smaller clumps may merge into a larger clump and this smaller spacing is no longer seen. A second explanation could be that as the lengthscale predicted by the sausage instability indicates only the fastest growing mode of fragmentation, it is possible that there is
5.2: PERIODIC SPACING OF CLUMPS

Figure 5.1: Herschel column density map of F357.588 with contours outlining the clumps identified along the filament when $N_{\text{step}} = 0.2 \times 10^{22}\text{cm}^{-2}$.

A second fragmentation lengthscale that produces larger clumps as well as a shorter lengthscale that produces smaller clumps. Another interpretation could be that as the filament was formed, it may have been less dense when it started to fragment, resulting in a larger wavelength of fragmentation being present at early times, when these clumps were formed.

To ensure that these peaks in the histograms are statistically significant, we compare them to the distribution of nearest neighbour distances we would expect if the clumps were randomly spaced along the filament. This was done by drawing a histogram of 1000 clumps placed randomly along a line. To ensure that the typical spacing between the clumps in the filament and this line are equivalent, we divide the length of the
5: FILAMENT FRAGMENTATION

Figure 5.2: Histograms of the distance from one column density peak to the next along the filament F14.182. The difference in height of the contours drawn to identify the column density peaks is varied from $N_{\text{step}} = 0.2 \times 10^{22} \text{ cm}^{-2}$ to $N_{\text{step}} = 0.7 \times 10^{22} \text{ cm}^{-2}$. KS tests show that there is a probability of less than a 5% that these distributions arise from peaks randomly distributed along the filament. The two core spacings identified here are 1.25′ and 2.25′.

All but one of the linear filaments show a characteristic spacing between the cores. F321.620 does appear to have a typical spacing of 2.75′, however the K-S test gave a probability of more than 5% that this was due to randomly spaced cores and so it is not included in Table 5.2. Eleven of the 22 linear filaments also show a second characteristic spacing. These spacings can be compared with $\lambda_{\text{max}}$ and $\lambda_{\text{eff}}$ to see if...
they match the predictions of the sausage instability.

5.3 Radial Profiles of Filaments

In order to find $\lambda_{\text{max}}$ we need to find the central density of the filaments so $H$ can be calculated. We also need to estimate the radius of the filaments to see if the filaments lie in the regime $R >> H$. These quantities can both be constrained by examining the radial profiles of the filaments.

Arzoumanian et al. (2011) found that the width (FWHM) of filaments within the Giant Molecular Clouds Aquila, Polaris and IC5146 is 0.1pc. However these smaller filaments within clouds are thought to form as a result of turbulence. The larger filaments containing strings of IRDCs along their length may be formed in an entirely different manner by the movement of the spiral arms through the galaxy (see Section 4.3.1). Jackson et al. (2010) estimated the radius of the Nessie nebula to be 0.5pc by examining the extinction of the Nessie nebula, giving it a width of 1pc, much larger than the width of the filaments examined by Arzoumanian et al. (2011). The radial profile of the Snake nebula was examined by Johnstone et al. (2003) and found to have $R_{\text{flat}} = 0.1pc$ giving it a FWHM of $\sim 0.3pc$.

5.3.1 Plummer-Like Profiles

The widths and central densities of the filaments can be constrained by fitting a Plummer-like profile to the radial profiles of the filaments. Plummer profiles (Plummer 1911) have been used to model the radial density profiles of filaments by e.g. Nutter et al. (2008); Arzoumanian et al. (2011); Malinen et al. (2012) as Plummer profiles have a flat inner region with a sharp drop in density at large radii, as observed in the radial profiles of filaments by these authors. The Plummer profile is given by
Table 5.1: The columns give (1) the name of the filament, (2) the typical spacing between cores, (3) the typical spacing between the larger cores (where appropriate), the spacing predicted by the sausage instability due to if the filament is dominated by thermal perturbations (4) or turbulent motions (5), the kinematic distance to each filament (6) and the three dimensional velocity dispersion (7).
5.3: RADIAL PROFILES OF FILAMENTS

\[ \rho(r) = \frac{\rho_c}{[1 + (r/R_{\text{flat}})^2]^{p/2}} \]  

(5.3)

where \( r \) is the distance from the centre of the filament, \( R_{\text{flat}} \) is the radius of the inner part of the filament where the density is constant and \( p = 5 \). However as \( p \) determines the rate at which the density decreases at large radii and [Ostriker (1964)] predicted that \( p = 4 \) for an isothermal cylinder, we leave \( p \) as a free parameter (hence the term Plummer-like profile). As we have the column density, not the volume density, we can write the Plummer-like profile in terms of the column density as

\[ N_{\text{H}_2}(r) = \frac{A_p \mu_{\text{H}} \rho_c R_{\text{flat}}}{[1 + (r/R_{\text{flat}})^2]^{(p-1)/2}} \]  

(5.4)

where

\[ A_p = \frac{1}{\cos i} \int_{-\infty}^{\infty} \frac{du}{(1 + u^2)^{p/2}}. \]  

(5.5)

The angle of inclination, \( i \), is not known for these filaments and so for simplicity we take \( i = 0^\circ \). If \( i \neq 0^\circ \) then \( \rho_c \) will be overestimated. If the filaments are randomly orientated, the average \( i \) will be \( 45^\circ \) and \( \rho_c \) will be overestimated by a factor of \( \sim 1.57 \). The greater the angle of inclination, the less likely it is that we will detect the filament in the first place, so we take the uncertainty due to the angle of inclination to be this factor of 1.57.

The solution to the integral in Equation [5.5] is given by the hypergeometric function, \( _2F_1 \) and hence \( A_p \) is given by

\[ A_p = 2 \left[ u_{_2F_1} \left( \frac{1}{2}, \frac{p}{2}; \frac{3}{2}; -u^2 \right) \right]_0^\infty. \]  

(5.6)
Finding Radial Profiles

We can fit a Plummer-like profile to the radial profile of the filaments to find the central density and radius of the filaments. The column density radial profiles can be found from the *Herschel* column density maps obtained for each filamentary structure by plotting the column density of each pixel along lines running perpendicular to the filaments. However in order to find lines perpendicular to the filament, we must first define the central axis of the filament. In a simple linear filament, this will simply be the major axis of the filament, however some of the filaments have a more snake-like shape and deviate away from the major axis.

It is possible to use the list of SDCs obtained from the MSTs to define the filament. As each SDC has a position associated with it (the position of peak opacity) we can use these positions to fit a polynomial to define the filament axis. As previously mentioned, not all of the SDCs listed will be part of the filament, so any SDC that does not appear to belong to the filament (determined by eye) is excluded from this analysis. We decide to fit a polynomial of order 3 to these positions as this is the minimum order required to describe the shapes of the filaments. Using higher order polynomials did not significantly alter the shape of the axis defined and so we elect not to use higher orders. Figure 5.3 shows the axis defined in this way for one such filament.

Once the filament axis has been defined, it is possible to plot the column density as a function of the distance from the centre of the filament. Cuts are taken across the filament, perpendicular to the filament axis, allowing the column density to be plotted for each pixel along this cut. As the filaments contain several cores spread along their length, radial profiles are taken at many different points along the filament so that the average profile will not be overly influenced by a large core or any gaps that may exist. As the resolution of the column density maps is 18”, we take the radial profiles every 18” along the filament.
5.3: RADIAL PROFILES OF FILAMENTS

Figure 5.3: Column density map of F299.158 with boxes showing the location of the SDCs extracted with the MST sub-tree and a line showing the polynomial used to describe the filament axis.

As we can see from Figure 5.3, the column density peak may not lie exactly along the polynomial defining the filament axis. We therefore set $r=0$ to be at the column density peak for each radial profile. We then take the mean column density at each radius to obtain the mean radial profile for the filament as shown in Figure 5.4.

Equation 5.4 is then fitted to the mean radial profile using the MPFITS package (Markwardt 2009) with $A$, $R_{\text{flat}}$ and $p$ as free parameters, where $A = \frac{A_p \rho_c}{\mu m_H}$ and $a$ is the size of 1” in m if $R_{\text{flat}}$ is given in arcseconds. $A_p$ can be computed numerically to constrain $\rho_c$. The distance to the filament must be known to find $a$ and hence estimate $\rho_c$. The results of this fit are shown in Table 5.2, along with the FWHM of the Plummer profile - the ‘width’ of the filament.

We find that the steepness of the radial profiles varies between 1.1 and 3.8, approaching but not reaching the result expected for an isothermal cylinder ($p=4$ Ostriker 1964)). Arzoumanian et al. (2011) found that the radial profiles had a steepness of $1.5 < p < 2.5$ for the filaments within giant molecular clouds. Malinen et al. (2012) found that the Taurus molecular cloud has filaments with $1.5 < p < 3$. If $p < 4$ the filament is not isothermal, indicating the presence of a temperature gradient with cooler gas in the
While most of the filaments we study do have density profiles consistent with these results, some of the filaments appear to have steeper profiles than expected. This could be a further indicator that such large-scale, isolated filaments have a different formation process to filaments within molecular clouds or it could be due to differences in their environments. It is also possible that the wide range in $p$ could indicate different stages in the evolution of the filaments, for example we might expect the profile to become steeper as the filament condenses.
5.3: RADIAL PROFILES OF FILAMENTS

<table>
<thead>
<tr>
<th>Filament</th>
<th>A</th>
<th>R_{flat} (&quot;)</th>
<th>p</th>
<th>FWHM (&quot;)</th>
<th>\rho_c (10^{-17} \text{kgm}^{-3})</th>
<th>n_c (10^3 \text{cm}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>F299.158</td>
<td>0.02</td>
<td>18.4</td>
<td>3.4</td>
<td>32</td>
<td>0.74</td>
<td>0.4</td>
</tr>
<tr>
<td>F320.234</td>
<td>0.06</td>
<td>25.5</td>
<td>2.8</td>
<td>54</td>
<td>3.2</td>
<td>1.9</td>
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<tr>
<td>F321.620</td>
<td>0.06</td>
<td>15.5</td>
<td>2.7</td>
<td>36</td>
<td>2.8</td>
<td>1.7</td>
</tr>
<tr>
<td>F329.090</td>
<td>1.70</td>
<td>3.0</td>
<td>1.5</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F330.287</td>
<td>0.42</td>
<td>5.1</td>
<td>1.1</td>
<td>58</td>
<td>3.2</td>
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</tr>
<tr>
<td>F338.098</td>
<td>0.06</td>
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<td>2.8</td>
<td>38</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>F342.222</td>
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<td>4.3</td>
<td>1.3</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.26</td>
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<td>3.1</td>
<td>52</td>
<td>20.7</td>
<td>12.4</td>
</tr>
<tr>
<td>F353.252</td>
<td>0.30</td>
<td>8.1</td>
<td>1.7</td>
<td>42</td>
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<td></td>
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<tr>
<td>F357.588</td>
<td>0.17</td>
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<td>2.3</td>
<td>36</td>
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<td></td>
</tr>
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<td>0.07</td>
<td>6.7</td>
<td>1.4</td>
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<tr>
<td>F6.446</td>
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<td>3.8</td>
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<tr>
<td>F8.543</td>
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<td>5.0</td>
<td>1.5</td>
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</tr>
<tr>
<td>F10.990</td>
<td>0.16</td>
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<td>40</td>
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<td></td>
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<td>F18.690</td>
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<td>3.6</td>
<td>28</td>
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<td></td>
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<td>1.7</td>
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<tr>
<td>F25.090</td>
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<td>14.0</td>
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<td>28</td>
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<td></td>
</tr>
<tr>
<td>F26.022</td>
<td>0.02</td>
<td>20.4</td>
<td>3.3</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F26.451</td>
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<td>18.8</td>
<td>3.8</td>
<td>30</td>
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<td>F36.383</td>
<td>0.15</td>
<td>10.4</td>
<td>2.2</td>
<td>32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Table to show the properties of the Plummer profiles fitted to the linear filaments and the central column densities calculated where the kinematic distances could be found.
5.4 Sausage Instability

Once $\rho_c$ has been found, we are now able to find $H$ using Equation 5.1 and hence the fastest growing wavelength predicted by the sausage instability. As we can only find $\rho_c$ for the filaments at a known distance, $H$ can only be found for these filaments.

5.4.1 Finding $\lambda_{\text{max}}$

$H$ is not only dependent on $\rho_c$, it also depends on the sound speed, $c_s$, within the filament. To find the sound speed we equate the average kinetic energy of the gas particles with the thermal energy of each particle given by the equipartition theorem, i.e.

$$\frac{1}{2} \mu m_H c_s^2 = \frac{3}{2} k_B T.$$  (5.7)

In Section 2.3.1 we found that the temperature within SDCs can be as low as 8K, increasing to the temperature of the surrounding medium at around 20-30K. As the filaments are made of both SDCs and warmer material connecting them, we take the temperature of the filaments to be 20K, giving $c_s = 461 \text{ms}^{-1}$. If the temperature is 10K, $c_s$ is reduced by a factor of $\sqrt{2}$, giving $c_s = 327 \text{ms}^{-1}$. $H$ would therefore also be reduced by a factor of $\sqrt{2}$. Although at the central densities observed the gas may be warmer than the dust, within the cores the density will approach $n \sim 10^5 \text{cm}^{-3}$, the condition for thermal equilibrium. As a result, the gas temperature may decrease to 10K within the cores with warmer gas between them. For this reason we take $T=20\text{K}$ as a typical value along the filament. We can now estimate $H$ and therefore find $\lambda_{\text{max}}$.

By taking the radius of the filaments to be the FWHM of the Plummer profile, we can see from Tables 5.1 and 5.2 the $R \sim 2H$. Although this does not satisfy the condition $R >> H$, as $R > H$ and $R$ is given by the FWHM of the Plummer-like profile, not the
outer edge of the filament which is hard to define, the relationship $\lambda_{\text{max}} = 22.1H$ is still a good approximation. If $R \ll H$, the fastest growing mode is given by $\lambda_{\text{max}} = 11H$, the result for an isothermal cylinder, so $\lambda_{\text{max}}$ may be shorter if the condition $R \gg H$ is not satisfied. The estimates for $\lambda_{\text{max}}$ are given in Table 5.1.

As discussed in Section 5.1, $H$ assumes that the motion of the gas particles is dominated by thermal motions not turbulence. If turbulence is important, $H$ can be found by replacing $c_s$ with either the velocity dispersion, $\sigma$, or the effective sound speed, $c_{\text{eff}}$. As $\sigma_{3D} > c_s$, $c_{\text{eff}}$ and $\sigma_{3D}$ are roughly equal and give similar estimates of $H_{\text{eff}}$. As we wish to consider both the turbulent and thermal motions of the gas, we calculate $H_{\text{eff}}$ using $c_{\text{eff}}$. The fastest growing wavelength is then found as before by taking $\lambda_{\text{max}}^{\text{eff}} = 22.1H_{\text{eff}}$, the results are given in Table 5.1.

The main sources of uncertainty in $\lambda_{\text{max}}$ are the estimates of the temperature and central column density, $\rho_c$. As previously discussed, if the temperature is decreased to 10K, $\lambda_{\text{max}}$ will be reduced by a factor of $\sqrt{2}$. The dispersion of central densities at the centre of the filament is $\sim 50\%$. If $\rho_c$ is doubled, $\lambda_{\text{max}}$ will decrease by a factor of $\sqrt{2}$. We therefore estimate the uncertainty on $\lambda_{\text{max}}$ is $\sim 50\%$. The estimates for $\lambda_{\text{max}}$ in Table 5.1 are consistent with the spacing between the cores. If there is a second typical spacing between the cores, $\lambda_{\text{max}}$ is consistent with the larger spacing in all cases except for F351.549.

Figure 5.5 compares $\lambda_{\text{max}}$ with the observed spacing of the cores, the points all lie near the line $\lambda_{\text{max}} = \text{observed spacing}$. In all cases, the difference between $\lambda_{\text{max}}$ and the spacings observed is less than 0.5pc. As $\lambda_{\text{max}}$ is consistent with the larger spacings observed, it may be that the shorter spacing represents further fragmentation of the cores. As the core becomes denser, if it is filamentary, the core itself may begin to fragment according to the sausage instability. In the case of F351.549, we note that this filament has an unusually small velocity dispersion of 588ms$^{-1}$, less half that of Clare Lenfestey
Figure 5.5: Plot comparing the observed spacing between the cores in the filaments and the spacings predicted by the sausage instability when considering only the thermal motions of the gas, $\lambda_{\text{max}}$. Where more than one characteristic fragmentation length is observed, we take the larger spacing of the cores except for F351.549 (see text). The dashed line is the line $\lambda_{\text{max}} = \text{observed spacing}$.

any other filament. As it is associated with the star formation region NGC6334, which has regions that are bright at 8\(\mu\)m, it may be that this filament is at a later stage in its evolution that the other filaments. The smaller spacing observed does not appear to exist along the entire length of the filament, it is confined to a short section with a higher density. It may be that this part of the filament has become more dense as the filament evolved and a shorter fragmentation length is present in this part of the filament. The longer fragmentation length therefore describes the fragmentation of the entire filament and as we measure $\rho_c$ along the entire length, $\lambda_{\text{max}}$ is consistent with the longer spacing.

$\lambda_{\text{eff}}$ does not appear to be consistent with the spacings between the cores. As the main source of error in estimating $\lambda_{\text{eff}}$ is $\rho_c$, we calculated the central density that would
be required for $\lambda_{\text{max}}^{\text{eff}}$ to be consistent with the larger spacings between the cores (see Table 5.3). In all cases except F351.549, the densities that would be required are at least a factor of 5 greater than those observed. Note that the central density, $\rho_c$, is the average density along the whole filament. The densities required are comparable to the densities in the centre of the cores. This discrepancy seems to suggest that the turbulent motions are not important in setting the fragmentation length scale, which is a surprising result. It suggests that the turbulent motions reflect relatively large scale motions which are not in fact well described as an equivalent local pressure.

Another interpretation could be that the non-thermal velocities of the particles have increased since the fragmentation lengthscale was set. As the filament collapsed, it is possible that an increase in density resulted in increased turbulent motions. Alternatively it may be that the assumption that the non-thermal velocity of HNC is equivalent to that of $H_2$ is not valid. The velocity dispersions are also measured in the cores and we assume this represents the velocity dispersion over the whole filament. This is unlikely to be the case as the fragmentation of the filament may increase the velocity dispersions within the cores. It is also possible that the central column densities of the filaments have been significantly underestimated. The central column density is averaged over the beam of the Herschel satellite and so the central column densities may be higher than observed. We have also neglected the role of external pressure on the filaments, which may have been higher at early times if filaments are formed by colliding flows, and alternative magnetic field configurations, which can play an important role on the fragmentation lengthscale (Nakamura et al. 1993).

### 5.4.2 Comparison with Literature

Jackson et al. (2010) found a typical spacing between the cores of 4.5 pc or 5′ at a distance of 3.1 kpc. This is roughly twice the spacing we find between the larger cores (2.5 pc). One reason for this could be that Jackson et al. (2010) identified cores from

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Table 5.3: The central densities estimated from the Plummer-like profiles and the central densities that would be required for $\lambda_{\text{eff max}}$ to match the largest core spacing observed.

<table>
<thead>
<tr>
<th>Filament</th>
<th>Required $\rho_c$ (cm$^{-3}$)</th>
<th>Estimated $\rho_c$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F299.158</td>
<td>$1.3 \times 10^4$</td>
<td>$1.9 \times 10^3$</td>
</tr>
<tr>
<td>F320.234</td>
<td>$1.4 \times 10^5$</td>
<td>$8.2 \times 10^3$</td>
</tr>
<tr>
<td>F330.287</td>
<td>$5.7 \times 10^4$</td>
<td>$8.2 \times 10^3$</td>
</tr>
<tr>
<td>F338.098</td>
<td>$9.2 \times 10^4$</td>
<td>$6.4 \times 10^3$</td>
</tr>
<tr>
<td>F351.549</td>
<td>$2.2 \times 10^4$</td>
<td>$5.3 \times 10^4$</td>
</tr>
<tr>
<td>F10.990</td>
<td>$8.5 \times 10^5$</td>
<td>$1.2 \times 10^4$</td>
</tr>
</tbody>
</table>

integrated HNC(1-0) maps at a resolution of 36$''$ and so it is possible that some cores were not resolved. The Herschel maps provide the best estimates of column density and so provide a more reliable way to trace the core locations. Jackson et al. (2010) also calculated $\lambda_{\text{max}} \sim 1\text{pc}$ and $\lambda_{\text{eff max}} \sim 4\text{pc}$, significantly smaller than our estimates of 2.3pc and 9.4pc respectively. The main reason for this is the difference in central density estimated: Jackson et al. assumed the central density was $10^4\text{cm}^{-3}$, significantly higher than the estimate given by the Plummer-like profile of $6.4 \times 10^3\text{cm}^{-3}$. Jackson et al. also took $T=10\text{K}$, giving $c_s = 327\text{ms}^{-1}$, which will also reduce the estimates of $\lambda_{\text{max}}$ and $\lambda_{\text{eff max}}$. Although $T = 10\text{K}$ and $\rho_c = 10^4\text{cm}^{-3}$ are reasonable estimates for cores, it is worth bearing in mind that the fragmentation lengthscale is set before the cores form. At the time when fragmentation started within the filament it is unlikely that the average temperature of the filament is comparable to the temperatures observed towards the centre of IRDCs.

Jackson et al. concludes that $\lambda_{\text{eff max}}$ gives the best prediction for the core spacing, in contrast with the results found here. Miettinen (2012) also find that the typical spacing between the cores in the filaments in G304.74+01.32 are best estimated by $\lambda_{\text{eff max}}$. 

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although this filament lies outside the area covered by the SDC catalogue so a direct comparison is not possible here.

Interestingly, [Heitsch (2013)] predict that the cores within Nessie should be a factor $\sim 2$ closer together than observed by [Jackson et al. (2010)], consistent with the spacing of 2.5pc we observe. Heitsch shows that for a central density of $1 \times 10^4 \text{cm}^{-3}$ and $T=10\text{K}$, a strong magnetic field is required to provide support to obtain a spacing of $\sim 2.5\text{pc}$. Although this prediction again uses temperatures and central densities that may not be appropriate for a filament that has not yet undergone fragmentation, this prediction serves as a reminder that magnetic fields may play an important role in the fragmentation of filaments. Unfortunately, uncertainties in the central density, temperature and magnetic field configuration of the filaments make it incredibly difficult to investigate their role here.

### 5.5 Summary

We investigate the nature of the fragmentation of the filaments by first identifying the cores within them. The cores are defined using the Herschel column density maps obtained in Section 2.3.2, with the minimum height at which a core is considered unique ($N_{\text{step}}$) is varied so that we can characterise the gaps between the largest cores and all the cores with a peak height of $0.05 \times 10^{22}\text{cm}^{-2}$ or more. This showed that all but one of the filaments show a characteristic spacing between the cores. In addition half the filaments show a second, smaller characteristic spacing when the smaller cores are included. We speculate that it may be that when we look at the smaller column density peaks, we detect smaller cores within the larger cores. The larger cores appear to fragment with a shorter characteristic length, possibly due to their higher density. These spacings are given in Table 5.1.

To compare the spacings found between the cores in the filaments with the fastest
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growing wavelength predicted by the sausage instability, we first find the central column density, $\rho_c$, and filament radius, $R$, by fitting Plummer-like profiles to the radial profiles of the filaments. The radial profiles are obtained from the column density maps by plotting the column density with respect to distance from the filament axis at several positions along the filament. These Plummer-like profiles show that there is a wide range in the steepness of the radial profiles, in some cases approaching the $p=4$ predicted for an isothermal cylinder by Ostriker (1964).

With estimates for the filament radius and central density, $\lambda_{\text{max}}$ and $\lambda_{\text{eff max}}$ were estimated, assuming the temperature of the filaments is 20K. We find that the spacing between the larger cores is consistent with $\lambda_{\text{max}}$, implying that the spacing between the cores is determined by the thermal motions of the gas, not the turbulence. The estimates for $\lambda_{\text{eff max}}$ are much longer than the observed spacing. The central density would need to be a factor of 5 or more larger to make $\lambda_{\text{eff max}}$ consistent with our observations. Lowering the temperature to 10K would not significantly decrease $\lambda_{\text{eff max}}$.

This is in contrast to the results by Jackson et al. (2010) and Miettinen (2012) who conclude that turbulent motions in the gas are important in determining the fragmentation length. It may be that the central density of the filaments was over-estimated by these authors and the temperature under-estimated. The fragmentation lengthscale is set before fragmentation takes place and hence the temperature may be warmer at such times. The central densities found using the Plummer profiles are typically lower than $10^4 \text{cm}^{-3}$, the value typically chosen when predicting the fragmentation length. While our observations indicate that $\lambda_{\text{eff max}}$ is inconsistent with the observed fragmentation lengthscale, further observations would be required to determine whether turbulence is important in the fragmentation of filaments.
6

Final Summary

In this thesis we first complete the Spitzer Dark Cloud catalogue to include the inner 20° of the Galactic plane, covering the GLIMPSEII region. This provided a complete survey of the infrared dark clouds in the region $|l| < 65^\circ$, $|b| < 1^\circ$ with 15,637 objects. By using Herschel data we were able to construct column density and temperature maps for the Galactic plane, providing column density maps of all the SDCs.

The column density maps of the SDCs were used to find the relationship between the foreground emission at $8\mu$m, $I_{\text{fore}}$, and the total $8\mu$m emission along the line of sight, $I_{\text{MIR}}$, for each SDC. We were able to confirm that the empirical relation $I_{\text{fore}}/I_{\text{MIR}} = 0.54$ is valid across the Galactic plane and, where possible, we recalculate the $8\mu$m opacity for each object to account for small changes to this relation. The column density maps were also used to clean the SDC catalogue to remove any artefacts by comparing peaks in the column density to the $8\mu$m extinction. This gave a sub-set of 8113 SDCs that have been associated with a column density peak, 52% of the initial sample. We note that we may not be able to detect a column density peak for SDCs with an equivalent radius of less than 20″ as the resolution of the column density maps is 18″. This is particularly true in regions with high background, where small increases in emission may become lost.
The SDC catalogue allows us to compare the properties of the SDCs in different regions in the Galactic plane. The Galactic centre is a particularly interesting region due to the unique conditions present. We find that SDCs towards the Galactic centre tend to have slightly higher temperatures and higher column densities than SDCs in other regions. This may be due to an increase in turbulence or thermal support in this region. This trend is also seen in SDCs towards other star-forming regions in the Galactic plane, implying that IRDCs are affected by their immediate surroundings.

The SDC catalogue has also allowed us to search for large-scale structure within the Galactic plane using a minimum spanning tree algorithm. This algorithm detected 88 different structures by tracing SDCs that are projected nearby on the sky. The majority of these structures are parts of complex networks of filamentary structures and are likely to be part of larger molecular clouds. Seven structures appear to be hub-filaments, with a central dark or bright hub (at 8µm) with several filaments radiating away. Eight structures appear to have a bubble morphology, we speculate that such structures are formed by stellar winds or supernovae expanding through the ISM. The remaining 22 structures are described as linear and appear as isolated strings of SDCs, similar to the Nessie nebula. We find that filamentary structures tend to be parallel to the Galactic plane. This is particularly true of the linear filaments. We speculate that this is due to the passage of spiral shocks through the ISM, forming ‘Bones’ (Goodman et al. 2013) along the leading edge of the spiral arms.

Observations of the HNC(1-0) line towards three or four clumps in seven linear filaments were made using MOPRA. The velocities of the clumps were consistent along the lengths of the filaments in all but one of the filaments, implying that they belong to a single structure. In F329.090, the velocities and appearance at 8µm and in column density indicate that this may be two filaments overlapping. Further observations would be required to resolve this. These observations were used to find the distances to the filaments and to find the velocity dispersions of the clumps.
We investigate the fragmentation of the 22 linear filaments identified by the MST algorithm and compare our findings to the predictions of the sausage instability. We find that all but one of the linear filaments have clumps that are regularly spaced along the length of the filament. We also find a second characteristic spacing for 11 of the filaments, we suggest the shorter characteristic spacing is due to further fragmentation of the clumps formed by the sausage instability.

To predict the spacing we expect the clumps to have, we first estimate the radial density profile of the filaments using a Plummer-like profile. We find the steepness of the radial profiles varies from $p = 1.1$ to 3.8, approaching, but not reaching, $p = 4$ expected for isothermal filaments. The Plummer-like profiles give the central density of the profiles, allowing us to predict the wavelength of the fastest growing mode according to the sausage instability, $\lambda_{\text{max}}$. We were also able to use the velocity dispersions to predict the fastest growing mode in the case where turbulence dominates the thermal motions on a large scale, $\lambda_{\text{eff max}}$. We find that the spacing we observe between the clumps is consistent with $\lambda_{\text{max}}$, implying that it is the thermal motions of the gas, not the turbulent motions, that dictate the scale of fragmentation in the filaments. We find that the central densities would need to be at least 5 times greater than observed for $\lambda_{\text{eff max}}$ to be consistent with the spacings observed. Such densities are comparable to the densities observed in clumps, unrealistic for a filament before fragmentation begins.

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Future Research

The MIPSGAL (Carey et al. 2005) and MIPSGALII (Carey et al. 2009) surveys cover the same region as the GLIMPSE and GLIMPSEII surveys, providing data at 24µm and 70µm. Point-like sources at these wavelengths represent young stars, so it will be possible to use this data along with the Herschel data at 70µm to investigate the association of these point-like sources with the SDCs. Peretto & Fuller (2009) found that 20% of the SDCs in the original catalogue contain 24µm sources, however this analysis has not yet been extended to the new SDCs.

By using data at longer wavelengths we could constrain the high-wavelength tail of the spectral energy distribution. It is also possible to obtain data at a higher resolution than the Herschel observations at 500µm (36″). This could be done using data from e.g. the ATLASGAL at 870µm (19″) (Schuller et al. 2009) or SCUBA2 at 450µm (7.5″) and 850µm (14.5″) (Holland et al. 2013). This additional information would improve the estimates of the column density and the temperature, providing more accurate maps of the SDCs and filaments.

Further observations of the cores within the linear filaments using e.g. MOPRA would enable us to confirm whether all of the filaments are indeed coherent structures. The velocity information of the HNC(1-0) line allowed distances to be estimated for five
filaments, this could be extended to include all 22 filaments. This would allow the observed spacings between the cores in the filaments to be compared with the sausage instability to determine whether turbulence affects the fragmentation of the filaments in a larger sample.

Filaments have been observed with thinner filaments radiating away from the main filament at right angles (Sugitani et al. 2011; Hennemann et al. 2012). It may be that mass falls onto the main filament along these smaller filaments. There is also some evidence to show that filaments may be contracting radially, increasing the density in the centre of the filament (Kirk et al. 2013). It would be interesting to map one or more of the filaments using a molecular line that traces the dense gas (such as HNC(1-0)), obtaining the velocity structure within the filaments. It would then be possible to investigate the motion of the gas and better understand how filaments evolve.

The magnetic fields of filaments may play an important role in the fragmentation of filaments. Magnetic fields could support the filaments against fragmentation and thus slow down star formation. The sausage instability has been adapted to include a variety of magnetic fields, including an axial magnetic field (Nagasawa 1987) and helical magnetic fields (Nakamura et al. 1993). On the other hand, the magnetic field of the Galactic plane could influence the formation of the filaments, making them more likely to form along the magnetic field lines. Polarisation measurements by Sugitani et al. (2011) indicate that the magnetic field in the Serpens filament is perpendicular to the filament axis. Similar observations of the linear filaments in our sample could constrain the effect of the magnetic field on the filament fragmentation.
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