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From Stars to Superplanets: The Low-Mass Initial Mass Function in the Young Cluster IC 348

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ABSTRACT

In this paper, we investigate the young cluster IC 348. Using a new and innovative method for the spectral classification of late-type objects, we focus on the low mass population of this cluster in order to detect the different formation and evolutionary stories of substellar objects. This provides compelling observational evidence for different formation and evolutionary histories for substellar objects formed in isolation versus as companions.

1.1 Introduction

As the existence of substellar and low mass stars has been discovered only recently, these cosmic objects have been the subject of intense investigation by astronomers. Compared to the Solar neighborhood and older open clusters, younger clusters are an advantageous environment in which the study of low mass objects could be carried out. One of these young clusters is the young cluster IC 348 (see Figure 1.1) that is the subject of the current paper based on work presented in Najita et al. (2000). Functioning in the larger context of star formation in the Galaxy, this paper sheds light on a critical area of star formation, that is, formation of very-low mass and substellar objects. Further investigations in this field may challenge our understanding of the concepts of “star” and “planets” that were based on what we know as a planet or star in our Solar System.

The formation of stars, brown dwarfs, and planets is not the outcome of a single process, but a result of many processes that take place at the same time, such as processes that govern molecular cloud structure, subsequent gravitational collapse, disk accretion, stellar winds, and stellar mergers. Understanding the low-mass end of the stellar initial mass function is very important in understanding these processes overall. Stars in young clusters are much brighter due to their relatively young ages. This luminosity advantage has been used successfully to detect some low-mass cluster members with mass less than 2% of that of the sun. However, the attempts to study the low-mass IMF in younger clusters have stalled at the vicinity of the hydrogen limit.

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1.2 Observations

We developed an alternative method of spectral classification of low mass objects. In order to avoid the strong absorption by water in Earth’s atmosphere we used the Hubble Space Telescope (HST) Near Infrared Camera and Multi-Object Spectrometer (NICMOS) to carry out measurements. “NICMOS provides imaging capabilities in broad, medium, and narrow band filters, broad-band imaging polarimetry, chronographic imaging, and slitless prism spectroscopy, in the wavelength range 0.8-2.5 microns. NICMOS has three adjacent but not contiguous cameras, designed to operate independently, each with a dedicated array at a different magnification scale” (STScI 2002). This technique could, fortunately, be applied to study the cluster IC 348. Ground-based imaging of this cluster has detected a significant spatial structure. The richest stellar grouping is the so-called “a” subcluster with nearly half of the cluster members.

The cluster IC 348 has already been the subject of study of other research groups, and our work (Najita et al. 2000) is an extension to those studies. Using spectral classification techniques, their measurement of the IMF in IC 348 is complete to the deuterium burning limit (0.015$M_\odot$). Since a precise division between a brown dwarf and planetary regimes is unavailable, astronomers disagree whether the distinction should be made in terms of mass or formation history. Probably a final answer will not be attained within the near future.

In Najita et al. (2000), we obtained narrowband photometry for 50 fields in the IC 348a subcluster. The three field positions were chosen to avoid bright stars and to maximize area coverage. We observed a set of 23 standard stars in order to cover spectral types K2 through M9 to calibrate the nonstandard NICMOS colors. These spectral types have the kinematics and colors typical of Solar neighborhood disk stars. In order to observe the effects of lower gravity, we have observed
a few pre-main sequence stars.

Three of the recent studies of IC 348 (Herbig 1998, Luhman et al. 1998, and Luhman 1999) have examined regions surrounding and including IC 348a. We can use the overlaps in stellar samples to directly compare the previous results with ours. Comparison with the celestial coordinates reported in Luhman et al. (1998) typically resulted in disagreements of less than 1″.

As illustrated in Figure 1.2 from Najita et al. (2000), the mass function derived for the young cluster IC 348 is similar to that obtained for the Pleiades cluster previously by Bouvier et al. (1998), but also appears to contain a significantly higher number of brown dwarfs than are found around nearby, Solar-type stars. It appears that the formation and evolutionary histories of substellar objects in clusters like IC 348 is substantially different from that of objects found in relative isolation, such as in the case of the Sun.

Our work was conducted on a small part of the Galaxy. At this stage of our work, we have to assess to what extent the star formation processes in the subcluster IC 348 relates to the processes of star formation elsewhere in the Galaxy. This cluster is 100 Myr old which makes it fairly representative as it is relatively young. This quality makes this subcluster a very successful candidate in understanding stellar and substellar formation processes. It could also help us formulate more accurate definitions to the words “star” and “planet” which are the subject of a large debate among scientists working in this field.
1.3 Conclusions

As we have indicated above, star formation is not the outcome of a single physical process but of the interplay of many processes. By carefully understanding the structure and formation of this young cluster and by determining to which extent it is represents the general behavior of the Galaxy, we could form a better idea about star formation. The understanding of the formation of brown dwarfs is extremely important in determining where we have to draw the line between planets and stars. Our current study is one of the earliest studies that have been done on the cluster IC 348; our understanding of the whole range of processes that are responsible for stellar and substellar objects is not yet complete. However, the information that this study has made available to us is very critical.

1.4 References

Overview of the Implications of the Mass Function in the Arches Cluster

Kristen Frazier

ABSTRACT

We observed the Arches Cluster, one of the most massive young star clusters in the Milky Way. It is ten times larger than most other clusters observed in the Milky Way and located 25 pc from the Galactic Center (GC). It is an optimal source to study the formation of young stars in dense regions. We hope to use this cluster as a model for dense star forming regions outside the Milky Way. By observing the spatial distribution of star masses within the cluster and the segregation of masses from the cluster center, it is possible to create a model for the formation of young stars in regions of high density and intense physical conditions as found in the Galactic Center. It is theorized that many clusters actually form in the center of the Milky Way before evolving and segregating themselves to the distribution currently observed in the Milky Way. Observations indicate probable stripping of gas and dust by high stellar winds in the center of the cluster. These observations indicate tidal forces in the GC are highly influential in the evolution of the Arches Cluster.

2.1 Introduction

The close proximity of the Arches cluster to the Galactic Center presents obstacles for ground-based observers. Until technological advances increased the spatial resolution of our near infrared telescopes, stars in the Arches cluster could not be studied individually and remained hidden by 25,000 light years of dust. Dust scatters visible light, dimming the observations of far off objects. This is known as “interstellar extinction” (Smith 1999). Observations must also overcome the interference of light from nearby stars. Using the new Hokupa’a Adaptive Optics (AO) technologies on the Gemini North 8m Telescope and the Hubble Space Telescope, we (Stolte et al. 2002) found the Arches cluster to be a very interesting region of our Galaxy. See Figure 2.1 for an image from the AO system. With a density of $3 \times 10^5 \, M_\odot \, pc^{-3}$ the Arches cluster is the densest young star cluster known to date (Figer et al. 1999). It has the estimated mass of $10^4 \, M_\odot$, making it also one of the most massive young clusters known in the Milky Way and is located 25 pc from the Galactic Center (Stolte et al. 2002).

Because of its close proximity to the GC, the Arches Cluster is subjected to the “most extreme

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star-forming environment within the Milky Way" (Stolte et al. 2002). Steep gravitational fields, magnetic fields, and an intense radiation field lead to high dust and gas densities, turbulent motion within the cluster, and strong tidal torques. While the high gas and dust density is advantageous to the formation of stars, the gravitational and radiation fields impede young stellar development. Young stars form, but are then bombarded by strong stellar winds and tidal forces. The combination of these forces is violent yet we discovered that compared to other massive clusters with high mass stars, the Arches Cluster is more successful at forming stars than any other region in the Milky Way (Stolte et al. 2002).

2.2 Formation of Arches

The close vicinity of the Arches Cluster to the GC has us asking the question: “How many clusters actually form in the densest environment of the Milky Way?” (Stolte et al. 2002). Considering that 3/4 of young star clusters are located in the GC, we conclude that more clusters like Arches once formed in the GC then dispersed over time. Models of galactic evolution suggest that clusters forming in dense regions of the Galaxy are disrupted after their formation by strong tidal forces exerted in the GC (Portegies Zwart et al. 2001). Figure 2.2 shows the broad arching structure cased by tidal forces which give the cluster its name. Due to this influence, clusters disperse and their stars contribute to the Galactic Bulge (Kim et al. 1999). Observations of the Arches Cluster support this theory because of its location and estimated age of 2-4.5 million years (Stolte et al. 2002).
FIGURE 2.2. This image of the Arches Cluster and surrounding area is a combination of radio, infrared, and x-ray imaging. The arching structures are radio emissions and the inset box is an x-ray image of individual stars in the cluster. The cloud seen around the boxed point sources is a cloud of 60 million degree gas. From: Astronomy Picture of the Day http://antwrp.gsfc.nasa.gov/apod/ap010614.html

FIGURE 2.3. These images of the Arches Cluster and the Quintuplet Cluster were taken by the Hubble Space Telescope. You can see that both clusters have a very high stellar density. This makes comparisons between the two clusters possible. From: http://imgarc.stsci.edu/op/pubinfo/pr/1999/30/content/9930w.jpg
2.3 Evolution of Arches

The Arches Cluster's young age leads to its comparison with other young stellar clusters in the Milky Way. Figure 2.3 is an image of the Arches Cluster next to an image of the Quintuplet Cluster. Other young stellar clusters in the Milky Way have mass functions with a Salpeter slope (Salpeter 1955). The Arches cluster however has a flat mass function meaning that there is "an overpopulation of the high-mass end as compared to the 'normal' clusters" (Stolte et al. 2002). The Arches Cluster has a higher concentration of large masses than is observed in other clusters in the Milky Way. This fact poses an interesting problem—what causes this high density of high mass stars?

The cause of this abundance lies within the GC environment. The physical conditions are more advantageous to the development of high mass stars than in less dense regions of the Galaxy (Morris 1993). The general theory of star development relies on radiation pressure from growing stars to reverse infall effects of accreting stellar gasses (Yorke & Krugel 1977). This model can only make stellar masses up to 10 M\(_\odot\), but can be increased to 15 M\(_\odot\) if accretion takes place in a disk rather than sphere (Behrend & Maeder 2001). This still cannot account for the massive stars we find in the Arches Cluster and other clusters near the GC (Stolte et al. 2002). This is why a new understanding of star formation must be developed for clusters near the GC.

In developing such an understanding three physical aspects of star cluster formation were taken into account:

- accretion properties of individual stars
- mass segregation of star masses within the cluster
- spatial distribution of star masses.

As observed in the Arches Cluster, there is a tendency for high mass stars to form in dense star forming regions (Larson 1982). Because of this tendency, a model of GC clusters must reflect a dependence on the local density of gas. According to a study by Elmegreen (1999, 2001), the rate of gravitational collapse and cloud collisions is proportional to the square root of the local density. When local density is high, gravitational collapse and cloud collision rates are high. These collisions are essential to the formation of high mass stars (Stolte et al. 2002). The Arches cluster exhibits this behavior.

The physical properties of any star-forming region are such that lower-mass stars must form before high mass stars as the cluster evolves (Stolte et al. 2002). This is due to the UV radiation field that high-mass stars produce during formation. If low-mass stars did not form first in the evolutionary process, the radiation field from the massive stars would blow away all excess gas and dust leaving nothing to form the low-mass stars (Stolte et al. 2002).
2.4 Spatial Distribution of Stars in Arches

The spatial distribution of the Arches Cluster is the last physical aspect of the cluster to be examined. High-mass stars are pulled into the cluster center by gravitational affects while low-mass stars "flung" outwards (Stolte et al. 2002). This distribution of mass would be responsible for a flat mass function that steepens as you move radially outward. However, this is not observed in the Arches cluster. Tidal forces from the GC pull at the cluster causing deviations from the predicted mass function. It is predicted that in time the cluster will be torn apart completely by the tidal forces (Gemini 2002).

2.5 Conclusions

Our study found the concentration of mass in the Arches Cluster is indeed located at the center of the cluster. Likewise, the flat mass function of the cluster indicates the high probability of mass segregation in the cluster; high-mass stars concentrated in the center with low-mass stars on the outer edges. The fact that 2/3 of young clusters in the Milky Way display a flat mass function indicates this is a common evolutionary process for this cluster type and it is independent of the GC environment. However, the available instrumental resolution is not yet high enough to determine which mass segregation is due to cluster evolution or interaction with tidal forces in the GC.

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Binary Brown Dwarf Characteristics in the Pleiades Cluster

Ben Herbert¹

ABSTRACT

We present an argument that suggests the formation processes of Brown Dwarfs (BDs) and Very Low Mass (VLM) stars are distinct from the similar processes that form hydrogen burning stars. In particular, these objects were not observed with a separation greater than 23 AU, as opposed to the wide range of stellar mass binary separations. Also, their Initial Mass Function (IMF) appears to follow a slightly different trend. The implications of these findings show that the mechanism of BD formation is different from that of stellar formation in the Galaxy.

3.1 Introduction

A large portion of stars in the Galaxy, unlike our own sun, are not lone objects. In fact, looking at the Solar neighborhood, it appears that 57% of nearby G type (or Solar-type) stars have at least one hydrogen burning companion of lower mass. This number decreases to around 38% for small M type stars. This is likely due to the fact that as the size of the primary star (the more massive star in a binary system) goes down, the range of masses it can gravitationally hold in its grip also decreases. For example, a G type star can have a secondary companion in the mass range of G sized stars through planetary sized objects. A lower mass M type star (the smallest type of star that is H burning) will only be the primary in a system if its secondary is a smaller M or is sub-stellar – a much smaller range. Still, the properties of these stellar systems are similar. They exhibit a large range of separations that are determined by the dynamics and properties of the molecular cloud that led to their formation. Statistically then, the binary separations are not related to the size of the primary star if it is H burning.

Brown Dwarf (BD) and other Very Low Mass (VLM) star binary systems have slightly different qualities. By analyzing these objects’ orbits, eccentricities, and orbital periods, we can begin to understand how these “failed stars” formed, and how that process may have been noticeably different from the process that leads to the formation of hydrogen burning binary systems. Progress on such a study of objects in the Pleiades Cluster (see Figure 3.1) was recently reported in Martin et al. 2000.

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3.2 Identifying BD and VLM binary systems

The process of identifying BDs and VLM stars is a tedious one due to the objects’ dimness and relatively small sizes. The objects in our survey were detected using the HST instrument NICMOS (Near Infrared Camera and Multi-Object Spectrometer) and from ground based adaptive optics systems. Data was gathered by these instruments for 45 apparent BDs in the Pleiades Cluster, a very young star forming region at a distance of only 125 parsecs. The objects looked at in this study range from \( M = 0.09M_\odot - 0.045M_\odot \). The data were then used to make a color-luminosity plot to characterize the objects. When dealing with large star formation regions, like the Pleiades cluster, one uses the approximation that all of the stars are at the about the same distance to produce a H-R plot (see Figure 3.2). It is necessary then to test all of the objects to make sure that they are indeed cluster members. Perhaps the easiest test for membership detects the presence of Lithium in the spectra of an object. Stars with an apparent magnitude corresponding to a VLM star at the distance of the Pleiades should have Lithium in their spectra, due to their cool temperature. If a star in the background, one that is further away than the Pleiades and thus very dim, is found, it can be differentiated from a Pleiades BD because of the lack of Lithium in its spectra. The color-luminosity plot can provide a benchmark curve (similar to the Main Sequence curve in an HR diagram) to which other stars can be compared.

An important characteristic of many VLM objects is evident in this type of plot (Figure 3.2). Cool objects can feasibly have dust particles in their atmospheres, creating a sort of “stellar greenhouse effect”. This is shown by the dashed line in Figure 3.2. These objects’ temperatures are higher not because they have a larger mass, but because the dust grains in their atmospheres insulate the stars the way carbon dioxide works in the Earth’s atmosphere.

The presence of binary systems can also be inferred by this plot. If the system is binary with similar companions and a separation too small to be resolved, the total luminosity of the point source observed will be greater than expected for any given color. The resulting curve parallel to the VLM star bench mark curve was observed in the data, indicating the presence of binary systems (this is demonstrated in Figure 3.2 by the open pentagons that are significantly above the solid lines).

3.3 Brown Dwarf Binary Characteristics and their Implications

Past studies of the Pleiades cluster revealed a multiplicity frequency of Solar–type stars consistent with a survey of the Solar neighborhood. Hence, this study of the Pleiades should be a representative sample of stars in this part of the Galaxy.

In this study, the only VLM binary found was not a member of the cluster. This, however, does not imply a scarcity of multiple VLM star systems in the Pleiades. As stated in Section 3.2, the presence of many binary systems consisting of similar VLM components can be inferred from the color-luminosity plot. Other projects, notably Steele & Jameson’s (1995), have concluded from spectroscopic temperature studies that 46% of Pleiades VLM stars are in multiple systems, though none have been resolved. Recall that the number of stars in multiple systems seems to diminish as
the primary star's mass decreases. Hence, the finding that perhaps a higher percentage of VLM systems than M star systems are binary, is interesting. This study, however, did not confirm that claim.

This study does however suggest another important peculiarity: the mass of the primary substellar object in a binary system could be an important factor in formation of the system. A VLM system has not been observed with a separation greater than 23 AU. Stellar binaries, however, exhibit a much larger ranges with a mean separation of 23 AU. Also, separations appear not to be dependent on the mass of the primary in true stellar systems. The obvious conclusion is that, perhaps, VLM formation has distinct, unique qualities that differentiates it from the processes of stellar formation. More precisely, the mass of the primary may correlate with the distance of the companion.

There are several possible explanations for this observation. For example, the orbits of long period BD companions can be perturbed by larger nearby stars in the cluster, launching them out of the system in their youth. Another theory is that the cloud fragments from which VLM stars form rotate slowly. This would lead to binary systems in which the components have fairly tight orbits. This is easy to understand from an energy standpoint; if the energy of a clump is small to begin with, lower energy orbits will develop as the clump collapses. Low mass clouds with high initial densities would also produce this result for the same reason. Perhaps, then, brown dwarfs have a tendency to form from high density, slowly rotating small clouds fragments. This is opposed to their H burning counterparts, which seemingly form in larger clouds in nearly any rotational and density state. It is logical to generalize this observation about binary BD formation to all BD formation.

3.4 The Sub Stellar IMF

The initial mass function (IMF) describes the probability of a star forming with any particular mass. The shape of the IMF determines how much of a region's mass is located in stars of a particular mass. The basis of the usual IMF is that there are more low mass stars than high mass stars. The bulk of the mass is then locked up in low mass stars. In our case of VLM stars, the situation seems different. This study predicts a sub stellar IMF (based on the power law definition of $dN/dM \sim M^\alpha$) with an $\alpha$ of $-0.53$, indicating that while there are more low mass brown dwarfs than high mass ones, the very low mass objects constitute a smaller percentage of total mass of the cluster (see Figure 3.3). Stellar $\alpha$s are generally below $-1$, fluctuating for each mass size but never going above this value. Once again, we can infer that the VLM formation process is similar but distinctly different from stellar formation. The fact that smaller and smaller mass BDs make up a smaller and smaller portion of the total mass in the Galaxy implies that the conditions in which they form may be more specific than those for low mass H burning stars, supporting our claim in Section 3.

FIGURE 3.3. The IMF of VLM stars in the Pleiades Cluster. It shows an $\alpha$ equal to $-0.6$, close the number found in this study of $-0.53$. Integrating this function gives a total mass of about 10 $M_\odot$ — only 1 to 1.5% of the total mass of the Pleiades. Still, this function can be used to predict nearly 250 BDs in the cluster. From Bouvier et al. 1998.

3.5 Conclusion

Our study of the multiplicity of VLM stars and BDs in the Pleiades Cluster has given insights into star formation in the rest of the Galaxy. These objects have slight but important differences from “true” star binary systems. Namely, BDs are consistently found in binary systems with fairly small separations between the companions. The IMF also appears to be unique for non H burning stars. The most important conclusion we have drawn from these observations is that the processes that lead to VLM star formation are not exactly the same as the processes that lead to H burning star formation. Indeed, molecular clouds with high density, low mass, slowly rotating “clumps” should house more BDs than the Pleiades. This implies that the density of BDs in the Galaxy is not constant but is instead highly dependent on the structure of the clouds that lead to their formation.

3.6 References

4

Multiplicity among Solar-type Stars in the Solar Neighborhood

Greg Chulsky

ABSTRACT

Using radial velocity measurements, we analyze the percentage of stars in the Solar neighborhood that belong to a binary system. For pre-main sequence stars, we find that this figure is 0.51 ± 0.06; for post-main sequence stars, it is 0.26 ± 0.04. We analyze how this and orbital characteristics affect theories of stellar evolution.

4.1 Introduction

Roughly half of the stars in the night sky are binaries, and the question naturally arises what the exact percentage is and what causes a star to be or not be part of a binary system. Also of interest are the particular orbital characteristics, and what bearing those have on our theories of stellar evolution, which will have to account for various observations. Among these are:

- the distributions of orbital eccentricities—which systems are brought into circular orbits and which are “stretched” into eccentric orbits
- orbital periods – which systems orbit close together and which are far apart
- mass ratios – whether stars tend to “pair up” with similar stars or stars of different types, which also affects theories on whether binaries are formed together or become bound later on
- correlations between different orbital characteristics – which characteristics are affected by the same phenomena
- the frequencies of singles, doubles, triples, etc., which reflects on how dense the formation regions for these systems are and how likely particular stars are to get gravitationally bound.

The predictions of the theory will have to account for tidal circularization, mass exchange, peculiar proportions of various elements, etc.

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4.2 Methods

The measurements were performed with CORAVEL (Figure 4.1), a radial velocity scanner. Operated by the Geneva observatory, it measures radial velocity by comparing the observed spectrum of a star with a physical mask. A Swiss telescope being built at La Silla will be dedicated to the same tasks as CORAVEL, but will probably perform it better. This will spell doom for CORAVEL.

4.3 Duplicity of Stars in the Solar Neighborhood

From a sample of 164 stars from Gliese’s catalog, the number of stars that are in a multiple system is found to be 0.54 ± 0.06 for pre-main sequence stars. This means that about half the pre-main sequence stars in the Solar neighborhood are part of a double star system. This number, however, appears to drop off with age, and only 0.26 ± 0.04 of post-main sequence stars are binaries. This may mean that binary stars “come apart” with age, or it may mean that the amount of stars joining into binary systems has been increasing. The first supposition can easily be checked — it would require that a large fraction of young binaries be distant, so that tidal effects would move them even farther apart (much like the Earth and Moon) until external forces (gravity from other stars) eventually dominate their motion. This effect should be most noticeable in dense stellar neighborhoods, as the external forces there are more significant. The second supposition would mean that there are more stars presently than before forming in dense
regions such as dark cloud complexes – dark cloud complexes are denser, making the stars more likely to bind together gravitationally.

4.4 Orbital Characteristics

The orbital periods of the stars fit a bell curve amazingly well, with an average period of 180 years (Figure 4.2). For stars of one $M_\odot$, this corresponds to a separation of just over 100 AU. Stars with periods between 11 and 1000 days have an average eccentricity of $0.31 \pm 0.04$; tidal effects make the orbits of stars with periods of under 11 days very circular, while stars with periods greater than 1000 days are very susceptible to external forces (Figure 4.3), so the first group (medium-length periods) seems to reflect the original binary-forming conditions – stars from that group are less likely to have their orbits modified. This eccentricity appears rather high for objects forming together in a disk – objects forming together should form as two parts of one rotating body, leading to more circular orbits – so it is possible that this is telling us that many binaries become gravitationally bound some time after they are formed.

FIGURE 4.3. Eccentricity distribution in the G-dwarf sample. (a) $P_{\text{circ}} < P < 1000 \text{d}$, a bell shaped distribution. (b) $P > 1000 \text{d}$, without (hatched) and with (white) corrections for detection bias. Solid line shows $f(e) = 2e$ normalized to $N = 34$. From Duquennoy & Mayor (1991).

4.5 Mass Ratios

The mass ratio \((q = M_2/M_1, M_2 < M_1)\) distribution (Trimble 1974, 1978) has two peaks of almost exactly the same height, at 0.25 and 0.95, implying that most stars in binary systems are either of approximately equal mass or differ by a factor of 3 to 4. One interpretation of this (Abt & Levy 1978, Trimble 1978) is that the former group is either stars that became gravitationally bound later on in their life or systems where mass transfer occurred, and that the latter group is stars that formed from the same disk. If this is correct, the latter group should have lower eccentricity orbits. Scarfe (1986) points out, however, that Trimble's sample is heavily biased by selection and evolution, so such speculations are premature. It appears that if the biases are taken into account, the lower of the maxima is the only one likely to be real (Scarfe 1986, Halbwachs 1986, 1987; see Figure 4.4).

4.6 Conclusions

We have a sample of 164 stars as a result of a long (13 yr. and ~ 4200 measured velocities) unbiased search. The percentage of stars gravitationally bound to other stars seems to drop off with age, which could mean that stars are now forming in more localized regions than before (e.g. dark cloud complexes), or that most binaries eventually separate. It seems that most binaries join at an early age, but the measured eccentricities are high enough to imply that the stars do not form together.

4.7 REFERENCES

Multiplicity of Pre-Main Sequence Stars in Southern Star-Forming Regions

Elizabeth Bass

ABSTRACT

Multiplicity in stars and the variation in frequencies of multiple star systems lack sufficient explanation. Ghez et al. (1997) surveyed pre-main-sequence stars in three dark cloud complexes and found that the frequency of multiple star systems was over twice that found in Solar-type stars in the Solar neighborhood. These results were compared with surveys of the multiplicity of other dark cloud complexes, and the percentage of multiple star systems was similar. Dark cloud complexes are star forming regions which are more dense and have a higher rate of star formation than the giant molecular clouds from which Solar-type stars in the Solar neighborhood formed. We propose two possibilities which account for the difference between the Solar-type and pre-main-sequence stars: the environment in which the stars formed and the evolutionary process of stars. Each of these possibilities has an impact on planetary formation, which will be discussed later.

5.1 Introduction

Speckle imaging as well as direct images were used in the K-band ($\lambda \sim 2.2\mu m$) multiplicity survey of the dark cloud complexes by Ghez et al. (1997). Speckle imaging involves taking multiple pictures with short exposure times of an object in order to avoid the blurring due to turbulence in the atmosphere. The three dark cloud complexes that we studied were Chamaeleon, Lupus and Corona Australis. These regions are at distances ranging from 130–200pc. An image of the Chamaeleon complex is shown in Figure 5.1.

In 104 sources surveyed, we detected 29 multiple star systems. Not all were binary systems. Two triple star systems were detected. This data was then compared with a previous multiplicity study carried out on some of the same regions by Reipurth & Zinnecker (1993) which was done at red optical wavelengths ($\lambda \sim 0.9\mu m$). What was discovered from this was that more multiple star systems were detected with the infrared survey. This is because cooler objects, such as pre-main-sequence stars, tend to emit light in infrared wavelengths and the dust in these dark cloud complexes causes extinction.

The results from the multiplicity survey of Lupus, Chamaeleon and Corona Australis (a com-

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FIGURE 5.1. This is a picture of Chamaeleon, one of the dark cloud complexes studied in the multiplicity survey of Ghez et al. (1997). Dark areas of dust can be seen at the top and lower left of the image. From http://antwrp.gsfc.nasa.gov/apod/ap020609.html.

Companion star fraction of 0.54 ± 0.06) were compared with the proportion of multiple star systems of two other dark cloud complexes, Taurus and Ophiuchus, found in surveys conducted by Ghez et al. (1993), Leinert et al. (1993), and Simon et al. (1995). The companion star fractions were similar (Ophiuchus was 0.50 ± 0.12 and Taurus was 0.58 ± 0.08). We conclude that dark cloud complexes produce roughly the same fraction of multiple star systems. Because the fractions were similar, more general conclusions can be made about star formation in dark cloud complexes.

5.2 Caveats

Before going further, it should be noted that we were limited in our ability to detect multiple star systems. All of our findings are for multiple star systems with a separation range of 15–1800 A.U. If the stars were too close to each other, the glare makes each star indistinguishable. The systems are also undetectable if they are aligned along our line of sight. If the stars are further than 1800 A.U. apart, then it is more challenging to tell if the stars are part of a multiple star system. To get a sense of what 1800 A.U. is, consider our Solar System. 1800 A.U. is about 45 times the radius of Pluto’s orbit, yet the distance to the nearest star is around 150 times greater than this. It is very likely that there were more multiple star systems that went undetected, even though a significant number was found. So, the actual companion star fraction is probably higher than what was found.
5. Multiplicity of Pre-Main Sequence Stars in Southern Star-Forming Regions

![Diagram showing the multiplicity of stars as a function of separation. The diagram includes data points for Tauri stars, Solar-type stars, and main-sequence stars.](image)

**FIGURE 5.2** This diagram illustrates the differences in fractions of multiple star systems in pre-main-sequence stars and Solar-type main sequence stars in the Solar neighborhood. In the diagram, it can be observed that the fraction of companion star systems in the pre-main-sequence is around twice that of the Solar-type stars (0.54 ± 0.06 in pre-main-sequence and 0.26 ± 0.04 in Solar-type stars). From Ghez et al. (1997).

5.3 Comparison with the Solar Neighborhood

The companion star fraction in dark cloud complexes was then compared to the fraction found for Solar-type stars in the Solar neighborhood (within 20 pc). The multiplicity of Solar-type stars was investigated by Duquennoy & Mayor (1991) by observing radial velocities of stars. The companion star fraction they found was 0.26 ± 0.04. Here is where a significant difference arises. Dark cloud complexes have a companion star fraction that is over twice that in the Solar-type stars. The diagram in Figure 5.2 provides an illustration of that difference.

5.4 Discussion

The next issue is explaining the cause of the difference between the multiplicity of the Solar-type and pre-main-sequence stars studied. One possible explanation is that each group of stars formed in a different environment. Dark cloud complexes are not like the molecular clouds that the stars in the Solar neighborhood formed within, they are denser and have a higher rate of star formation. Therefore, a different percentage of multiple star systems developed in each area. Durisen & Sterzik (1994) propose that the frequency of binary systems among pre-main-sequence stars in regions with low temperature is higher. They support their claim by citing that most Solar-type stars likely form in high temperature, high mass star forming regions. They point out...
that the frequency of binaries in Solar-type stars is less than that in low temperature, low mass regions such as the Taurus dark cloud complex.

The second explanation is an evolutionary effect. With this, all young stars tend to start out in a high frequency of multiple star systems. As these stars evolve, some of the systems break up to form isolated stars. Systems with three or more stars would be especially susceptible to being disrupted (more so than binaries). The disruption of the systems would cause the multiplicity to decrease, thus accounting for the lower frequency of multiple star systems in older stars.

With either case, there is an effect on planet formation. If multiple star systems actually develop more frequently for all stars and then have a tendency to break up, then these disruptions could disrupt the circumstellar disk. If so, one could ask if planets could still form nevertheless. Also, one could speculate about the possibilities of the formation of planets within a binary system, if a system did not break up. Or, if star formation is different in different environments, how will planet formation be different for those environments?

The difference in multiplicities between regions and even the frequencies of multiplicities themselves show that there is still much to be discovered. Not all stars are binaries in the dark cloud complexes. And if multiple star systems do break up as stars evolve, why are there still binaries in the Solar neighborhood?

5.5 REFERENCES

6

Low Mass Star Formation in the Upper Scorpius OB Association

Jennifer Seiler

ABSTRACT

95 low-mass pre-main-sequence stars in the Upper Scorpius OB association were studied through their astrometric, spectroscopic, and photometric properties, to determine their ages, and the processes by which they formed in order to determine the history of the Association. It was determined that all stars in the sample group in the Upper Scorpius region are about 5 Myr old, (both low and high mass stars). This suggests that star formation was triggered by a shock wave from a supernova, because all star formation happened at once. The common age the fact that star formation is finished for all the stars in the association also suggests that star formation halted rather suddenly by the dispersion of the molecular cloud by strong winds and radiation from the massive stars.

6.1 Introduction

OB associations, as large collections of very young stars, and as the dominant birthplace of low-mass stars, are some of the best tools for the understanding of stellar evolution and the initial mass function. The Upper Scorpius region OB associations are a convenient source for the study of young, pre-main-sequence (PMS) stars. Firstly because, they are a part of the Scorpius Centaurus association group, which is the closest OB association to our Solar System (470 lyr away), and secondly because it is the youngest in the Scorpius-Centaurus group (with an age of 5 Myr). Lastly, the star formation process is already finished there (as indicated by the lack of dense molecular material surrounding the young stars), so it is at a perfect stage to be studied (with low dust, little variation in luminosity and temperature over time and among stars, etc.). The lack of gas and dust clouds also means there is very little extinction. Not much study has been done on low mass PMS stars because they are hard to distinguish from normal stars (with the exception of Classical T Tauri stars, which are minority among T Tauri stars, and are easily detected by their strong Hα emission). However, PMS stars are strong X-ray emitters (2-3 orders of magnitude brighter than main sequence stars of the same spectral type), because they rotate rapidly. Because of this, PMS stars were able to be separated from other field stars in the Upper Scorpius region by X-ray observations.

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![Map of our field of interest in the Upper Sco region](image)

**FIGURE 6.1.** Map of our field of interest in the Upper Sco region is marked by the thick solid line. Bright low-mass PMS stars are marked by large black dots, and fainter PMS stars are marked by smaller dots. Classical T-Tauri stars are marked by asterisks. High mass stars are gray circles. From Preibisch & Zinnecker 1999.

### 6.2 Data Collection

The Upper Scorpius association was observed by the satellite Hipparcos, giving initial astrometric data for 1215 stars, of which, 120 were determined to be members of the group. The ages of the high-mass main-sequence turnoff members were identified (on the HR diagram) to be 5-6 Myr old, with no evidence for a large spread among ages. This turns out to be the same age as the estimated age of the association.

32 low mass PMS stars were selected from over 200 X-ray sources in 60 deg$^2$ area from the ROSAT (ROentgen SATellite) All Sky Survey, all 32 were within a 24 deg$^2$ subarea of that survey and have lithium lines strong enough to determine them to be PMS stars by earlier empirically determined criteria. Another 78 X-ray candidates for PMS stars were selected from a spectroscopic survey over a 160 deg$^2$ area. This was so large in order to cover a spatially complete sample of the full area of the association. 39 of those 78 candidates matched lithium line criteria for PMS stars. In addition to these 71 identified PMS stars, 24 PMS stars identified in previous studies by spectroscopic and photometric data that fit in that 160 deg$^2$ area were also added to the study. Because of the wide range of the spectroscopic survey the sample of all 95 stars is said to be spatially unbiased (i.e. continuous, even, and complete) for all X-ray sources in the optical magnitude range of interest (10.5<B<14.5). This allows for the investigation of the spatial distribution of the stars and the line of sight depth of the association, in addition to the data helping us to understand photometric criterion for PMS stars, and extinction, luminosity, and temperature qualities of the stars. Understanding these things will help us to understand the processes by which these stars were formed, the IMF, and allow us to know more criteria for
further identifying low-mass PMS stars. See Figure 6.1 for a map of our survey region.

There was found to be no spatial relationship between low-mass and high-mass PMS stars, and the distribution was found to be roughly homogeneous. The line of sight depth of the association (by the parallaxes of members of the association) shows the depth to be about 30 pc, and with an average radius of 15 pc – this shows the association to be approximately spherical. The color-magnitude dependence was looked at for those stars characterised by their lithium lines. 31 of those 39 stars were found to lie well above the main-sequence line, confirming their status as PMS stars. To place the PMS stars onto the HR diagram, extinctions, luminosities and temperatures of the sample were measured. This is interesting for PMS stars because the relation between spectral type and temperature depends on surface gravity, making it different from main-sequence stars because of different burning processes and density. Temperature was measured as a function of spectral type and luminosity class. Extinction was determined by looking at the R-I colors of the stars, and intrinsic colors were determined as a function of both R-I color and temperature. Extinctions were found to be very small (A < 2 mag), with no spatial variation in the field. Based on these calculations, the stars may be placed on the HR diagram, and their stellar ages are derived based on already determined empirical PMS evolutionary tracks.

Taking into consideration errors from the spread of stellar distances (errors give an change in log L = 0.15), photometric errors (giving a change in log L = 0.12), and the possible existence of binary stars not resolved, and using the assumption of a 5 Myr age for all stars in the sample we find a band in the HR diagram in which 90% of the sample should lay. Indeed, only 9 out of 86 stars fell outside the selected region on the HR diagram (see Figure 6.2). Significantly fewer stars fit within bands with errors for other ages in the HR diagram (outside of 4–6 Myr). 5 Myr has the best fit and shows little evidence for any significant age spread. Ages were calculated for
6. Low Mass Star Formation in the Upper Scorpius OB Association

... each star in the field to look for a spatial age gradient. No evidence for a spatial age gradient was found. Observing the spatial dispersion of the sample, their ages, and their radial velocities there is evidence that the stars must have been in a considerably denser configuration during formation. This suggests that the association started as a dense cluster which expanded when it was caused to become gravitationally unbound. The total mass of all stars in the upper Scorpius region is estimated to be about 2350 $M_\odot$. The star formation rate was, thus found to be an order of magnitude higher than that of typical T Tauri associations, but comparable to the formation rate of the very dense Trapezium cluster. The high star formation rate combined with the small age spread, and the similar ages derived for low and high mass stars is an indication that star formation was triggered.

6.3 Discussion / Conclusion

The Scorpius-Centaurus association is surrounded by HI shells, which were created by supernova explosions and stellar winds. The oldest (largest) shell is centered around the upper region of the Scorpius-Centaurus association, around the Upper Centaurus-Lupus association, which is also the oldest subgroup of the association. The shock wave from the supernova which created this shell passed through the Upper Scorpius cloud 5 Myr ago. Such a large, slow shock wave could easily induce star formation by collapsing cloud cores. After the burst of star formation, something must have halted star formation to allow for such a small spread of ages for both the high and low mass stars. This could be explained by the many massive stars in the group which began to emit ionizing radiation and creating strong winds when they reached main sequence, thereby dispersing the molecular cloud and halting star formation. Also, 1.5 Myr ago the most massive star in the Upper Scorpius region exploded in a supernova and produced a shock wave which would easily have dispersed whatever cloud material was left in the group.

6.4 References

A Review ofExternally Illuminated Young Stellar Objects

Brendan Rehon

ABSTRACT

We present the data and observations of Bally et al. (1997) concerning externally illuminated young stellar objects (YSOs) in the Orion Nebula. These objects contain the archetypal protostar-circumstellar discs with an encapsulated central star and microjet. Due to stellar wind and ultraviolet radiation from O star θ¹ Orionis C, the YSOs have additional features aside from being protostellar accretion disk. YSOs contain ionized fronts, tails that narrow downwind from θ¹ Ori C, and arcs caused by excited [O III] and Hα being stuck between two shock fronts. YSOs occur in crowded clusters, like the OB association in Orion, and since OB associations produce the highest total of stars in our galactic neighborhood, perhaps YSOs are far more common than ever thought possible. If so, then there could be changes in how astronomers view traditional forms of stellar formation, planetary formation, and even the search for Earth-like extra-Solar planets.

7.1 Introduction

The Orion Nebula (M42) is a massive hotted for star formation—in fact, it is the closest HII region at 430 pc away (Warren & Hesser 1977). The primary radiation sources for this ionized hydrogen are two stars located in the Trapezium cluster. These stars, the young O stars θ¹ Orionis C and θ² Orionis C and, are surrounded by a flurry of protostellar objects. Laques & Vidal (1979) were the first to detect these young stellar objects (YSOs) in the Trapezium neighborhood, discovering seven distinct knotlike structures that emit brightly at the Hα spectral levels. Even since the discovery of the seven IV sources (as the structures were called), many more YSOs have been detected using radio telescopes like the Very Large Array and, later, with unprecedented detail by the Hubble Space Telescope (HST). Here we present the observations by Bally et al. (1997), compiled using HST, Wide Field Planetary Camera 2 (WFPC2), Faint Object Camera (FOC), and Faint Object Spectrometer (FOS) data.

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FIGURE 7.1. This is the Trapezium region as a color mosaic of images from WFPC2 HST observations of the Orion Nebula. Red is [N II], green is Hα, and blue is [O III]. Note the orientation and direction of the tails and ionized fronts. Also, note the existence of [O III] + Hα arcs in certain areas around θ¹ Ori C but not in others. From Bally et al. (1997).

7.2 Observations & Interpretation

Most of the Trapezium YSOs have a complicated structure, consisting of many ionized components. This can be seen in the following photo mosaics constructed by Bally et al. (1997). Figure 7.1 depicts how YSOs surrounding the star θ¹ Orionis C are almost comet-like in appearance with a bright "head" and an attached tail. The "head" of the YSO is a bright emission front that directly faces the star θ¹ Ori C, while the tail of the object faces radially outward from the star. These tails are somewhat triangular, generally narrowing and sharpening to a point as the tail extends farther outward. In addition to objects' ionized fronts and tails, some have hemispheric arcs which are concave toward the YSO, and which convexly face θ¹ Ori C (Bally 1997). These arcs are also strongly visible through the [O III] and Hα filters, demonstrating a significant amount of ionized gas emission in order to be visible against the bright nebula background.

While these young stellar objects have various sorts of external ionized features, they are actually just altered protostellar systems. Figures 7.2 and 7.3 highlight the internal structures within the young stellar objects. HST 2 (170-337) in the Corona Ori region (Figure 7.2) reveals a micro-jet emerging from the center of the illuminated YSO. In the third mosaic, dark, opaque discs
are visible within the YSOs. These discs are seen in silhouette against the background nebula light. Furthermore, looking at YSOs through the F547M filter (which shows continuum emission centred at 5446Å reveals the presence of central stars in about 80% of YSOs (Bally 1997). These dark discs are just the circumstellar discs in a protostellar system, which may expel jets like in HST 2 during the accretion process.

As it turns out, the stellar wind and radiation from θ¹ Ori C is what externally illuminates the YSOs. Figure 7.4 is a schematic diagram of the region containing the Trapezium stars, which contains several different “zones.” The first zone is the bubble containing the stellar wind, which is quite powerful for θ¹ Ori C. Within this hot wind bubble, there is an inner region dominated primarily by the drag force of the wind itself (ram pressure). The outer region is a hot bubble (at about 10⁶ K), that is consequently dominated by thermal pressure (Weaver et al. 1977). Also present within and outside of this hot wind bubble are regions of photoionization containing far ultraviolet (FUV) and Lyman continuum radiation. There is also a surrounding layer of neutral gas dubbed the “neutral lid” located between the viewer and the HII region/hot wind bubble. Furthermore, this lid also separates the HII region from the molecular cloud region.

As the diagram in Figure 7.5 tries to show, the interactions between the stellar wind and FUV radiation create the primary features of YSOs. The results of a paper by Johnstone, Hollenbach, & Bally (1998) proved that the mere presence of Lyman continuum and FUV radiation interacts with a YSO by creating a protective layer of ionized material also forming a low velocity spherical disk wind-away from the circumstellar disk. This, along with other UV radiation, is the source of the ionized fronts (i.e. the bright “head” or “crescent” that faces toward θ¹ Ori C) present in YSOs.

The appearance of YSOs depends specifically on the placement of the object within the various
FIGURE 7.3. Same as Figure 7.1, but for field containing HST 10. Red is [N II], green is Hα, and blue is [O III]. Note the opaque disc in the interior of the YSO. From Bally et al. (1997).

FIGURE 7.4. A schematic drawing of the area around the θ^1 Ori C wind bubble. Note the lack of [O III] + Hα arcs past the ‘stellar wind’ radius, and the lack of ionized YSOs past the “hot wind bubble” radius. The appearance of a YSO depends more on proximity to θ^1 Ori C than on intrinsic properties of the YSO. From Bally et al. (1997).
regions of the Orion Nebula. For instance, the existence of [O III] and Hα arcs depends on where within the hot wind bubble the YSO is located. Bally et al. (1997) propose that these arcs occur when ionized front (IF) wind reaches an equilibrium with the ram pressure of the \( \theta \) Ori C stellar wind. When this equilibrium forms, two different shocks are created. A dense layer forms between the two shocks, which can be excited by UV radiation or heated stellar wind, creating [O III] and Hα arcs. Since these arcs occur when equilibrium in a primarily ram pressured environment is possible, they can’t be found anywhere beyond the inner region of the wind bubble.

7.3 Discussion

The idea that nearby existing stars can drastically affect protostellar systems implies that stellar formation might not just be a question of how individual clouds of dust and gas accrete to become stars. Not even in the most massive star forming regions do stars ever form at exactly the same time. If stars can affect protostars with stellar wind and UV radiation, does that hinder, benefit, or just complicate the subsequent star forming process?

This question is compounded by the relative frequency of star formation occurring in places just like the Trapezium cluster. The Trapezium YSOs are not just protoplanetary discs but are a product of the relatively cramped Trapezium cluster. As Bally et al. (1997) note after completing a census of the nearby star forming regions within 500 pc of the Sun, at least 90% of younger stars
in our Galaxy are being formed in four major OB associations much like Orion. In such relatively crowded conditions, larger stars could wreak havoc on the development of much smaller stars. This might contradict existing ideas of what star populations should be. According to our current theories, sun-like populations should be plentiful since they form easily by accretion processes and have longer lifespans. But if most stars are formed in OB associations, smaller stars could be frequently destroyed, resulting in a discrepancy between observation and theory.

If the radiation and stellar winds of larger stars during their formation destroy smaller stars, and if throughout the universe this is the case, this could destroy hopes of finding Sun-like stars with intact protostellar discs. Do ionization fronts effectively protect the central circumstellar disk or does the stellar radiation break apart these discs before planets can even form? Such radiation, even if it does not destroy the protoplanetary disk, could also prevent life from developing on extra-Solar planets.

7.4 Conclusion

The YSOs in the Orion Nebula consist of exterior and interior components. The exterior ionized components, such as ionized front, downwind tail, the [O III] + Hα arc, depend entirely on where a YSO is with respect to a nearby star. The interior components are intrinsic, a circumstellar disk with a central star formed by accretion. At the same time, we do not know the length of time that must pass before the external forces, such as stellar wind and radiation, can alter those interior components as well. By understanding that relationship, the science of star formation could become much simpler.

7.5 References

The Episodic, Precessing Giant Molecular Cloud Outflow from IRAS 04239+2439 (HH 300)

Mansi Manoj Kasliwal

ABSTRACT

This paper presents a discussion of the results of the first set of detailed molecular-line maps of the giant Herbig Haro flow HH 300 from the young stellar object IRAS 04239+2436 (Arce & Goodman 2001). HH 300 significantly affects cloud kinematics and deposits about $10^{43}$ ergs of energy over approximately 11% of B18W, its parent molecular cloud. We also calculated a steep power-law mass-velocity relation ($dM/dv \propto v^{-\gamma}$ where $\gamma \sim 4$ for outflow velocities in the range of 0.75-1.85 km s$^{-1}$) and believe that this is on account of evolution of outflow mass kinematics. There is significant observational evidence for the episodic and precessing nature of the bow shock-shaped clumps in this outflow. We think that this is best explained by tidal interactions between the source and its stellar companion. Our observations suggest that HH 300 plays the role of self-regulation by reducing the probability of further star formation in this region.

8.1 Introduction

A Herbig-Haro (HH) object is a nebulus knot that delineates the shock arising from the interaction of a high-velocity flow of gas ejected by a young stellar object (YSO) and the ambient medium (Arce & Goodman 2001). With the recent discovery of many parsec-scale HH objects (the biggest outflow is HH 111 which is 7.7 pc long), we present the significant impact of the episodic and precessing HH 300 outflow on the dynamics of a substantial volume (~11%) of B18W, its parent dark cloud in Taurus. These colossal sized flows can accelerate entrained gas and transfer momentum and energy into the cloud to produce molecular outflows.

We acquired data using the on-the-fly mapping technique at the National Radio Astronomy Observatory 12m telescope on Kitt Peak, Arizona in December, 1998. We combined data for multiple molecular line transitions ($^{12}$CO(1-0), $^{12}$CO(2-1), $^{13}$CO(1-0), $^{18}$CO(1-0)) to probe a range of densities and account for velocity dependent opacity of the $^{12}$CO line, thereby increasing the precision in our calculations. We observed red-shifted HH objects (HH 300A, HH 300B, HH 300C),

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each with a bow shock-like morphology and all close together in a region about 1.1 pc long and 0.3 pc wide. We obtained a steep power-law mass spectrum and attempt to explain this based on the evolution of the outflow mass kinematics. Due to contamination from another cloud along the same line of sight and same velocities, we were not able to observe details of the blue-shifted lobe. Only one small blue-shifted knot (HH 300D) about 0.02 pc from the source was observed.

We hypothesize that the observed discrete clumps in space and time are due to episodic mass ejections. Lines drawn from the source to each of these clumps (which have different orientations over a range of 29° on the plane of the sky) sweep out a cone suggesting precession. The source of this outflow is IRAS 04239+2436, the lowest luminosity YSO yet observed to exhibit CO overtone bands (Greene & Lada 1996). A cometary nebula surrounding the source, a jet on the blue shifted side of the HH flow along the symmetry axis of the nebula, and a stellar companion have been observed in the near-infrared (Reipurth et al. 2000). Tidal interactions with its binary companion might explain the precession.

8.2 Discussion

Our most important concerns while analyzing the data were determining the inclination, opacity correction and ambient cloud contamination. We were able to reliably correct for the velocity dependent opacity and cloud emission. Unfortunately, no proper motion study of the HH 300 optical knots was done and we made only radial velocity measurements. Without information about the tangential velocity, we were not able to compute the inclination angle. However, the smaller the angle between the flow’s axis and the plane of the sky, the longer the observed projected size of a flow will be for a given flow length. Since HH 300 is observed to be a relatively giant molecular flow, we estimate the angle to be relatively small and between 5° and 15°.

Assuming that all parts of the flow have roughly the same inclination angle, we calculated the slope of the power-law mass-velocity relation independent of this angle. This relationship gives the amount of mass moving in a given velocity bin. The outflowing mass decreases as outflow velocity increases. Quantitatively,

\[
\frac{dM(v)}{dv} \propto v^{-\gamma}
\]  

(8.1)

We carefully accounted for the high opacity of 12CO line at low velocities. Since it is optically thick here, we only “see” the surface cloud and thus, have to correct for underestimation of mass. Underestimating mass at the lower velocities would lead to an underestimated slope of mass as a function of velocity and result in an underestimation of \( \gamma \). We calculated \( \gamma \sim 4 \) for outflow velocities in the range of 0.75-1.85 kms\(^{-1}\) and \( \gamma \sim 7.8 \) for higher outflow velocities. The majority of observations, made without this correction, (Zhang & Zheng 1997, Smith et al. 1997) and analytical studies (Matses & McKee 1999) suggest \( \gamma \sim 2 \). The most compelling reason that might explain our high \( \gamma \) value is outflow evolution. Over time, the slope reduces because the outflow consists of more and more slowed down gas. Thus, \( \gamma \) increases as the outflow ages. We also expect that outflows in denser mediums will decelerate more rapidly if momentum was to be conserved. Perhaps, future observations of outflows for a variety of ambient density distributions and time histories of the outflow would contribute more evidence to this hypothesis.
8. The Episodic, Precessing Giant Molecular Cloud Outflow from IRAS 04239+2439 (HH 300)

![Image of contour map](image)

**FIGURE 8.1.** Integrated intensity contour map of $^{12}$CO(1-0) emission to show the discrete location of clumps in the HH300 outflow. If lines are drawn emanating from the young stellar object to the clump, they sweep out a cone indicating the episodic and precessing nature. Also note that, based on extinction, the B18W molecular cloud can be identified in this image in regions with minimum background stars. From Arce & Goodman 2001.

The episodic and precessing nature of the outflow would also affect $\gamma$ by modifying the density and velocity distribution of the gas since each ejection may entrain new material from the ambient medium or reaccelerate gas that was already in motion. We observe that not only does HH 300 have discrete clumps in space and velocity, but the position of the outflow lobe axis with respect to the source varies over a range of 29°. We also observe that there is a peak in momentum at each red-shifted clump. The lines emanating from the source to the clump appears to sweep out a precessing cone like structure (refer to Figure 8.1). This all suggests that these eruptions are episodic and if we look at the widest spread clumps and assume that they form the edges of the precessing cone, we can calculate the precession period as twice the difference in the eruption age of the two clumps (eruption age is a measure of how long ago the clump was ejected from the source). The source of the outflow is a 42 AU binary and we believe that tidal interactions between the circumstellar disk of the source and its stellar companions are responsible for the precession. This raises important questions about the probability of formation of multiple star systems and even, general differences between stellar nurseries that have mostly multiple as compared to mostly single star systems.

To examine the quantitative significance of the effects of the outflow, we studied the velocity dispersion of the cloud as a function of position. In regions of clumps, we found multiple peaks in a plot of antenna temperature as a function of velocity - one set arising from cloud emission and another from both cloud emission and molecular outflows (refer to Figure 8.2). This clearly indicates that the outflow put a substantial amount of gas in motion. Our calculations indicate that the total energy of the outflow ($10^{43}$ ergs) is comparable to the cloud's total turbulent kinetic energy ($kM\delta v^2 \sim 10^{44}$ ergs). Moreover, this energy is of the same order of magnitude
as the cloud’s binding energy ($GM^2/R$). Molecular outflows can potentially disperse significant fractions of these molecular clouds greatly diminishing the likelihood of further star formation. We estimated the power of the outflow as energy over the dynamical age (which is a measure of how long the outflow has been active). This power is only a factor of ten less than the power required to sustain magnetohydrodynamic balance i.e. the input power needed to support a molecular cloud in equilibrium. Since this would support it against gradual gravitational contraction, it also reduces the probability of further star formation.

FIGURE 8.2. Relative comparison between regions of the cloud affected and unaffected by the molecular outflow. All six spectra plot antenna temperature on the vertical axis and velocity on the horizontal axis. The extra peak in three spectra due to the effect of the outflow is indicated by a vertical solid line and indicates the significant impact of the outflow on cloud kinematics. From Arce & Goodman 2001.
8.3 Conclusion

We can conclude that it is characteristic of giant, precessing HH outflows to have the potential to modify the velocity and density structures not only of their host core but also of their host cloud (Arce & Goodman 2001). On one hand, outflows significantly affect the cloud gas kinematics and contribute to cloud dispersion since their energy is comparable to the cloud’s binding energy. Clearly, this reduces the probability of further star formation in that region. On the other hand, the outflow adds material to the ambient medium that would eventually help in star formation. In summary, giant flows may contribute to the chemical rejuvenation of clouds, the generation of turbulent motions, and the self-regulation of star formation (Reipurth et al. 1997). The significant effect of molecular outflows from young stellar objects on parent molecular clouds exhibit yet another remarkably interdependent and intertwined cycle in nature.

Acknowledgements: I would like to thank Dr. Martha Haynes and Karen Masters for their constant encouragement, patient help and guidance.

8.4 References

Millimeter Dust Emission from Northern Bok Globules

Dave Cohen

ABSTRACT We present the results of a 1.3 mm continuum study of 59 Bok Globules in the Milky Way. Based on their emissions in different wavelengths, we divided the globules into four separate groups. Our observations show that indeed each group has distinctive properties and represents a different stage in star formation. By calculating individual distances to each globule, we were able to show that globules are not completely isolated objects, but rather usually associated with larger cloud complexes. Our 1.3 mm study provided evidence that most Bok Globules form one or two stars with masses of ~ 0.5 M☉, and that the typical lifespan of a globule is 10⁶ years.

9.1 Introduction

One of the most fundamental problems in astronomy is understanding the star-formation process. When, where, and why stars form are questions that we strive to answer in our quest to understand why we're here. The physical processes involved in star formation are exceedingly complex and difficult to study since they happen on such a large time-scale by human standards. Before we can even hope to understand the process as a whole, we must be able to understand the process in its simplest form – in the formation of small relatively isolated low-mass stars. These processes are free from the complicating effects of large numbers of newly formed stars, with associated stellar winds and outflows (Launhardt & Henning 1997).

Bok Globules (named after their finder Bart Bok) are the simplest molecular clouds in the Milky Way. The globules are small, dark, and generally spherical with diameters of about 0.7 pc and masses of about 10 M☉ (Bok 1977). These regions are relatively isolated and do not experience the complex gravitational and magnetic fields which occur in larger molecular clouds. It is estimated that there are approximately 10⁹ Bok Globules in our Galaxy (Clemens et al. 1991). The globules appear optically as dark regions that obscure background stars (see Figure 9.1), and it was not originally clear to astronomers what they were. Recent studies of globules have indicated that at least a fraction of them are sites for active star birth (Reipurth 1983). Observations have also indicated that many globules have dense cores, which are believed to be the sites where new stars are being formed, or may represent protostars themselves (Martin & Barrett 1978). Despite these studies, little is known about the incidence and properties of such dense cores. A millimeter study

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9. Millimeter Dust Emission from Northern Bok Globules

FIGURE 9.1. The Bok Globule, Barnard 68, does not allow background stars to be seen at optical wavelengths. From http://antwrp.gsfc.nasa.gov/apod/ap990511.html.

is very well suited to look at dense cores, because at these wavelengths, thermal dust emission remain optically thin (Launhardt & Henning 1997).

9.2 Observations

We used the “Catalogue of small, optically selected molecular clouds” (Clemens & Barvainis 1988) to select globules for our study. The catalogue contains 248 small dark clouds that are generally isolated and north of −30° declination. Our criteria for selection included the presence of cold point sources, and high visual extinction, since we wanted to search for star forming cores. We chose 39 globules to study, and divided these into 4 groups as follows:

- Group 1: which we identify as candidates for internally heated star forming cloud cores.
- Group 2: which we identify as candidates for pre-protostellar cores or extremely young protostellar cores.
- Group 3: which we identify as candidates for more evolved young stars.
- Group 4: globules with no associated point sources.

Our 1.3mm survey was performed during four observing runs between December 1992 and March 1994 using the 15-m SEST (Swedish-ESO Submillimeter Telescope) at La Silla, Chile, and the 30-m IRAM telescope at Pico Veleta, Spain.
An important task was to derive the distances of the globules. Most Bok Globules are too small to apply normal techniques, so we had to turn to other methods. Since it is clear that Bok Globules must have formed from a more extended component of the interstellar medium, we made the assumption that the globules are not isolated, but rather mostly associated with larger molecular clouds. Thus, if a globule is located near a known molecular cloud complex and has a similar velocity, we assigned the distance of the known complex to the globule (see Figure 9.2). In doing this, we were able to associate about 90% of our sample to larger molecular clouds, and obtained an average distance of 500 pc. This high percentage indicates that our method works well in general, and supports the theory that globules have formed from larger molecular clouds and were later separated (Launhardt & Henning 1997).

We looked at the average derived masses for each of our four groups, and found these measurements to be consistent with our assumptions about the evolutionary stage of each group. In general, the average density of the globule decreased from group 1 to group 3. We found another progression in looking at the detection rates of globule cores at 1.3 mm wavelengths (which is indicative of a dense cold core). From classes 1, 2, 3, and 4, we found detection rates of 94%, 20%, 7%, and 20% respectively. Based on these observations, we estimate that 15-30% of Bok Globules recently formed stars, while 30-65% either never formed stars or formed them long ago. Assuming an average stellar mass of 0.5 $M_\odot$, the lifetime of a protostellar core is calculated to be about $2.5 \times 10^6$ years (Wilking et al. 1989). We assumed that all globules form stars at some point in their evolution, and determined an upper limit of $5 \times 10^6$ years for the average lifetime of Bok Globules after being separated from larger molecular clouds.
9.3 Conclusions

Our observations show that the globules are not completely isolated; most are loosely associated with larger molecular clouds from which they probably broke away. Most of the globules tend to form one or two 0.5 M$_\odot$ stars sometime in their lifespan, while only the least massive globules dissociate fast and never form stars. Interestingly, the more massive globules tend to form multiple low-mass stars, rather than more massive stars. In general, about 5-10% of a globules mass in transformed into stars, while the rest probably dissipates later. Additionally, we estimate that the average lifespan of Bok Globules is $5 \times 10^6$ years after they were separated from larger molecular clouds and before they dissipate. Finally, the lifetime of the globules seems to be shorter than that of the stars they form. It is suggested therefore that many of the observed isolated stars were probably formed by Bok Globules. In fact, our own Sun is relatively isolated, and its mass is consistent with what we'd expect to form from a globule. It is thus feasible to think that the Sun and the rest of the Solar System could have once originated from a Bok Globule.

9.4 References

Molecular Clouds and Infrared Stellar Clusters in the Far Outer Galaxy

Chris Scannell

ABSTRACT

We will study star formation in the far outer Galaxy (defined to be at Galactic radii greater than 13.5 kpc) by studying molecular cloud properties determined by a CO emission survey, Infrared Astronomical Satellite (IRAS) Point Source Catalogue data, and follow up imaging in K-band (2.2 μm). We study a region of 63 molecular clouds, in which we found 11 stellar clusters exhibiting star forming behavior similar to that of clusters local to our own region of the Galaxy. We also find that although the rate of global star formation is significantly less due to the different environment at far outer Galaxy distances, the mass spectrum and star formation per unit mass of star forming regions are similar to the rest of the Galaxy.

10.1 Introduction

Outside a Galactic radius of about 13.5 kpc, the rate of star formation in the Milky Way Galaxy exhibits a sharp decline. In this same region, the overall density of molecular gas shows a definite decline, but molecular clouds (Blitz, Fich, & Stark 1982; Wouterloot & Brand 1989; Mead, Kuter, & Evand 1990) with Population I stars and H II regions (Chromey 1978) show proof of stellar formation in these regions. While the levels of star formation are negligible compared to the inner Galaxy, the nature of the far outer Galaxy (namely the lower metallicity and gas density) may lead to different methods of star formation via different properties of the molecular clouds (Snell, Carpenter, & Heyer 2001). Surveys of the region to be studied are limited, but include an extensive study of CO emissions by Wouterloot & Brand (1989) using IRAS, identification of H II regions by Fich & Blitz (1984), Brand & Blitz (1993) and Rudolph et al. (1996), near-IR imaging by Kobayashi & Tokunaga (2000) and Santos et al. (2000), and especially a CO survey by the Five College Radio Astronomy Observatory (FCRAO) (Heyer et al. 1998) that detected 246 far-outer galaxy clouds (Heyer, Carpenter, & Snell 2001).

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10. Molecular Clouds and Infrared Stellar Clusters in the Far Outer Galaxy

<table>
<thead>
<tr>
<th>IRAS Source</th>
<th>$T_{\text{max}}$(^{12}\text{CO}) (K)</th>
<th>$V_{\text{LSR}}$(^{13}\text{CO}) (km s$^{-1}$)</th>
<th>$\Delta V$(^{13}\text{CO}) (km s$^{-1}$)</th>
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10.2 Survey of outer Galaxy molecular clouds

We mainly studied a 60 degree sub region of the FCRAO CO survey, and isolated sources with CO emission velocities between -110 kms$^{-1}$ and -59 kms$^{-1}$, corresponding to Galactic radii between 13.5 and 28 kpc (Snell, Carpenter, & Heyer 2001). Specific criterion of flux and color were used to identify star forming regions, and 11 final regions associated with far outer Galaxy molecular clouds and star forming sites were chosen for detailed study. 10 of these regions were imaged in the near-IR K-band by Wainscoat & Cowie (1992), producing $5' \times 5'$ mosaics corresponding to a region between 9 and 15 pc across. 10 Sources were mapped in CO using the FCRAO in 1998 (Snell, Carpenter, & Heyer 2001).

By these surveys we arrived at the properties of the molecular clouds, see Table 10.1. The velocity, diameter, and mass are determined by the CO observations, with masses computed by integrating the CO intensity, assuming optically thin conditions. A factor of 1.36 is included in the mass estimate to account for elements heavier than hydrogen that do not appear in the survey (Snell, Carpenter, & Heyer 2001). Far infrared luminosity of the regions is found using a formula from Casoli et al. (1986) using flux and kinematic distances. Several were found to have luminosities greater than $10^4$ $L_{\odot}$, most likely indicating a massive star forming site. Rudolph et al. (1996) provided further evidence by identifying H II regions using the Very Large Array.

Stars usually form in clusters, so we expected to find clusters in the IRAS point sources. They were identified in K-band images using the same criteria for identification employed by Carpenter et al. (2000) in his survey of W3/W4/W5, a local molecular cloud complex. Each mosaic contained at least one statistically significant cluster, with 11 total clusters found ranging from radii of 13.5 to 17.3 kpc (Snell, Carpenter, & Heyer 2001). Using magnitude comparisons with two local, well studied clusters, Mon R2 and Orion, we determined that the total number of stars in the largest far outer Galaxy clusters is twice that of Mon R2 and Orion, assuming that the initial mass function and extinction are similar (Snell, Carpenter, & Heyer 2001). This can also be compared to a survey of the W3/W4/W5 region of the Perseus arm (at radius 10.4 kpc) by Carpenter et
10. Molecular Clouds and Infrared Stellar Clusters in the Far Outer Galaxy

...al. (2000), with the conclusion that clusters are forming in far outer Galaxy with richness equal to that of a local cloud complex.

The molecular clouds in the far outer Galaxy are located in several distinct regions, and we can group about two thirds of the clouds into nine associations using the galactic (l, b, v) coordinate system (Snell, Carpenter, & Heyer 2001). The most massive and distant cloud was discovered by Digel, De Geus, & Thaddeus (1994) at a distance of 28 kpc. Based on optical H II regions explored by Kobayashi & Tokunaga (2000), there is strong evidence for massive star formation in this extremely distant cloud.

10.3 Mass spectrum

It is useful to develop the mass spectrum (graphic representation of the number of clouds vs. cloud mass found in the molecular clouds) of the far outer Galaxy because it may depend upon properties of interstellar gas that vary with Galactocentric radius (Snell, Carpenter, & Heyer 2001). Based on masses of the 246 clouds found by CO luminosities, the slope of the mass spectrum (α in dN/dM ∝ M^α) is about −1.88. A study conducted by Heyer et al. (2001) determined the mass spectrum slope of clouds in the nearby Perseus arm to be about −1.8, and a study by Scoville & Sanders (1987) found a slope of −1.61 for the mass spectrum of the inner Galaxy. Therefore, even though the clouds in the far outer Galaxy are 10-100 times less massive than structures in the inner Galaxy, they exhibit nearly identical mass spectrum slopes, where the number of clouds per mass bin increases at lower masses with the same rate. It is also useful to determine differences in global star formation averaged over the entire area, equivalent to the ratio of luminosity to mass. The far outer Galaxy with L/M = 1.2 is actually more active than the local W3/W4/W5 complex with L/M = 0.56. Based on both stellar clusters per unit mass and the luminosity to mass ratio, the clouds in the far outer Galaxy exhibit greater star formation activity than in a local complex. Although molecular clouds in the far outer Galaxy form at a lower efficiency, they are as efficient at forming new massive stars as inner Galaxy molecular clouds and we expect an order of 500 infrared stellar clusters at far outer Galaxy distances based on 2MASS Extended Source Catalogue Data (Snell, Carpenter & Heyer 2001).

10.4 Conclusion

Star formation in far outer Galaxy clouds does not differ much from that in local clouds like the W3/W4/W5 complex or inner Galaxy clouds. The lack of molecular clouds at far outer Galaxy distances can be attributed to less efficient formation from atomic gas, accounting for the low global star formation, but the mass spectrum is not much different. Stellar clusters form nearly identically to those locally, there is sufficient evidence of massive star formation, and star formation per unit mass is similar to that in the rest of the Galaxy.
10.5 REFERENCES

Supernovae in the Pleiades B1 Subgroup and the Origin of the Local Bubble

Kelley Hess

ABSTRACT

The Pleiades subgroup B1 was found to be an excellent candidate for the “smoking gun” of the supernova (SN) explosions which may have created the Local Bubble. The “smoking gun” theory relies on indirect evidence from which we can infer some event occurred in the past. From Hipparcos data, the trajectory of the subgroup shows that it passed through the Local Bubble within the past 10–20 million years, which corresponds to the approximate age of the bubble. An Initial Mass Function of the group shows that approximately 20 supernovae must have occurred during that time period. Later supernovae are responsible for reheating the medium in the Local Bubble and account for observed X-ray emissions. It is also possible that the formation of the Local Bubble is linked to that of Gould’s Belt, but we favor the scenario in which SN explosions formed it.

11.1 Introduction

Local is a relative term. Nowhere is this as evident as in the description of our lonely, boring corner of the Milky Way Galaxy. The sun’s “local” neighborhood extends between 80 and 200 pc and it includes hundreds of nearby stars. The space between is filled with hot, low density, X-ray emitting plasma. This collection of matter is known commonly as the Local Bubble (LB). Although this structure is not unique in our region of the Galaxy, its origin is unknown. There is evidence that the bubble may be related to the formation of Gould’s Belt, a chain of stars that formed 20–30 million years ago. Their formation corresponds to the estimated age of the LB. Even more indirect evidence points to the fact that the Local Bubble is the result of one or more supernova (SN) explosions.

Next door to our own LB is another superbubble known as Loop I (see Figure 11.1). It is an interesting structure to study because of its similarities to the LB. Their radii, age and rate of supernovae in the past are approximately equal, yet Loop I is still active, powered by approximately 40 supernovae, while the Local Bubble may have experienced about 20 supernovae in its history and is now virtually extinct. Where supernovae are still occurring in Loop I, active star formation continues. The LB however does not contain any supernova candidates. It seems

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possible that these two structures were caused by similar phenomenon, despite the lack of SN evidence in the LB. While investigating its origins, we must remember that the layout of the Solar neighborhood has changed in the past 10-20 million years due to the movement of objects. We can postulate that a stellar cluster of massive stars may have passed through the present LB region earlier in its lifetime, when its larger members were exploding supernovae. This provides the grounds in drive to search for a ‘smoking gun’ (Berghöfer 2001).

11.2 Pleiades B1 as a “smoking gun”

The youngest of four subgroups (B1) of the Pleiades group was identified as an excellent candidate for the “smoking gun” theory using data from the Hipparcos Space Astrometry Mission. The group was found to contain the right mass distribution for supernovae, a path which passed through the Local Bubble at the right time, and enough energy necessary to explain the observed X-ray emissions from plasma in the LB.

The stars observed by Hipparcos in Pleiades B1 are the youngest stars known to exist in the Solar
11. Supernovae in the Pleiades B1 Subgroup and the Origin of the Local Bubble

neighborhood. We study younger stars because they are related to the number of recent SNe that exploded at the appropriate time to form the LB. They are the remnants of a cluster where more massive stars existed in the past, but have since exploded as SNe. The majority of the stars in subgroup B1 range from 6-9 $M_\odot$, with the two largest stars still present having masses of 10-11 $M_\odot$. In order to estimate the IMF, we must make several assumptions:

1. The stars in the subgroup coevolved
2. All the stars of mass 6-9 $M_\odot$ were counted in the survey
3. The shape of the mass distribution curve for the subgroup is similar to the curve known to occur in the Solar neighborhood.

The result of these assumptions is a lower limit for the IMF of the subgroup because we acknowledge the possibility that some objects remain undetected. We find that approximately 19 SN explosions have already occurred. From the age of the cluster, we know that these SNe must have occurred over the past 10-20 million years. Therefore, Pleiades B1 had the SN explosions at the right time to create the Local Bubble.

In order for the SN in Pleiades B1 to have affected the LB, the subgroup's historical path must have intersected it. To calculate the trajectory, the velocity component with respect to the Local Standard of Rest was measured using Hipparcos data of the stars in the subgroup. Figure 11.2 shows the trajectory of the center of mass of B1 as it moved through the LB over the past 30 million years. With a suggested age of 20-30 million years, the most massive stars in Pleiades B1 would have exploded approximately 13 million years ago. This corresponds well to the estimated age of the LB: 10-20 million years. Figure 11.2 shows that at this time B1 was within the boundaries of the current LB. Due to the spread of individual positions of stars, it is possible that more massive members of the group passed (and exploded) closer to the center of the LB. Meanwhile some may have occurred completely outside of it (Berghöfer 2001).

11.3 The last SNe in the LB

Lastly, the current energy in the system of the LB must be accounted for. While some characteristics of the superbubble picture of the LB could be explained in ways, such as the sweeping of hot gases through the Solar neighborhood from nearby star forming regions, these theories cannot explain the presence of X-ray emissions from hot plasma in the LB. The best explanation for this observation is SN explosions. The fact that the X-ray emissions from the LB plasma medium are not homogeneous suggests that multiple SNe are responsible. From the energy of the X-ray emissions and using a cooling law developed by Kahn (1976), it is possible to obtain the timescale since the last SN explosion heated the medium within the LB. According to calculations, the last SN occurred around 10$^7$ years ago or perhaps as recently as 10$^6$ years ago. This is still consistent with the movement of Pleiades B1 group as it continued its journey through the LB. One of the massive B1 stars could easily have exploded within the bounds of the LB, inputting energy into system and thereby accounted for the leftover X-ray emission we now detect. In fact, this timescale corresponds to evidence found in the Earth's crust extracted from deep ocean
layers, where an increase in $^{60}$Fe indicates a SN explosion occurring nearby about 5 million years ago (Berghöfer, 2001).

11.4 Conclusion

Presently there are two theories designed to explain the formation of the Local Bubble. The first states that its formation is related to Gould’s Belt (Figure 11.3): A giant molecular cloud (GMC) collided with the galactic plane, triggering cloud collapse and the formation of stars. The 20° inclination of the string of massive OB stars that make up Gould’s Belt run parallel to the structure of the Local Bubble. During the collision gas was cleared out by the GMC, explaining the low density of gas in the LB. Finally, we observe the velocity of Gould’s Belt stars is decreasing as they recede from the galactic plane. However, from the evidence presented in this paper “we favor a scenario in which the LB was created by about 10–20 SNe about 10–20 million years ago” (Berghöfer 2001). In this theory, a shockwave swept molecular gas out from the center of the SNe explosions, leaving behind hot plasma and creating a bubble in the interstellar medium. Here the chimney-like structure perpendicular to the plane of the Galaxy can be attributed to the decreased ambient pressure at higher altitudes from the galactic disk. The velocity and IMF of Pleiades subgroup B1 leads us to believe it was the possible source of these SN explosions. In either case however, the most recent SNe occurring in the LB did not serve to reshape it, but their energy input causes the spatial fluctuations of X-ray emissions that we see today. Eventually the Sun will leave the LB, just as Pleiades B1 is passing out of it, but for now, studying its position
FIGURE 11.3. A cross sectional view of Gould’s Belt shows the 20° inclination with respect to the galactic plane. The sun is at the center of the graph, the galactic center is to the right in the direction of +x, and the disk midplane lies along the x-axis. From LeDrew (1999).

gives us a picture for how the structure of our local neighborhood formed.

11.5 REFERENCES