Chapter 1

Protostars and Outflows

1.1 An Introduction to Protostar Evolution

Out of the 100 billion or so stars in the Milky Way Galaxy, our nearest star, the Sun is considered to be a middle of the road main-sequence object with a surface temperature $\sim 6000$ K and spectral type of G2. Despite this, the Sun shares a common origin with all stars: they were all born in molecular clouds. Representing the denser parts of the interstellar medium, molecular clouds come in all shapes and sizes. From the massive giant molecular clouds ($\sim 10^{4-6} M_\odot$) to relatively small Bok globules ($< 10^3 M_\odot$), these regions possess sufficient density ($10^{2-3}$ cm$^{-3}$) for stars to form. However, these regions are supported against gravitational collapse by the presence of magnetic fields$^1$. For a neutral molecular cloud under magnetic support, the neutrals within only “feel” the field through the interaction of ionized particles, which are tied to the field. For sufficiently dense cores, cosmic rays alone dominate the ionization (McKee 1989) and so the weak ion-neutral coupling induces a systematic drift (or ambipolar diffusion) of neutrals with respect to the ions which separates the magnetic field from the neutral gas and allows the cloud to collapse via self-gravitation.

As the core contracts, the released gravitational energy is converted into thermal energy which allows the collapsing core to remain isothermal. As the core continues to contract, the interior temperature of the protostar becomes high enough for thermonuclear reactions to begin. With the conversion of hydrogen into helium, the resulting heat ($\sim 10^6$ K) and internal pressure

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$^1$Thermal and turbulent pressures are present as well, but magnetic fields play a far more important role in preventing core collapse.
are enough to halt contraction and achieve hydrostatic equilibrium. The hydrostatic core builds up its central mass via the accretion of material from the in-falling surrounding envelope. Before the onset of accretion, the mass of the surrounding envelope far exceeds that of the hydrostatic core. In the model of Shu, Adams & Lizano (1987), the rate of infall is constant \((\sim 1 \times 10^{-5} \, M_\odot \, \text{yr}^{-1})\) in time. The T Tauri phase will continue for another \(\sim 10^6\) years in which the star will continue to accrete mass from the remnant circumstellar disk.

Due to the extremely dense material surrounding newly-formed protostars, early researchers found it difficult to characterise the star formation process and constrain theory. However, the dusty circumstellar material surrounding the protostellar core becomes heated and re-radiates its thermal energy at infrared wavelengths. Therefore, it should not come as a surprise to learn that it is the amount of circumstellar dust surrounding a protostellar core which has been the key element in providing an evolutionary sequence. The currently favoured picture has been based on developments in wide field near-infrared detectors and sub-millimetre bolometers. For example, Class 0 sources (André, Ward-Thompson & Barsony 1993) are detectable for wavelengths > 10\(\mu\)m, usually in sub-millimetre continuum maps, while Classes I, II and III are classified on the slope \(\alpha_{IR} = d\log(\lambda F_\lambda)/d\log(\lambda)\) of their Spectral Energy Distributions (SEDs) for wavelengths long-ward of 2\(\mu\)m (Lada 1987; Wilking, Lada & Young 1989). Class I corresponds to sources with \(\alpha_{IR} > 0\), Class II with \(-2 < \alpha_{IR} < 0\), and Class III with \(\alpha_{IR} < -2\).

Class 0 objects \((t \leq 10^4 \, \text{yr})\) show compact centimeter radio continuum and/or sub-millimetre emission. They display a high ratio of sub-millimetre to bolometric luminosity which suggests the envelope mass exceeds that of the central stellar mass. Their SEDs resemble a single temperature blackbody with \(T \sim 15-30\) K. Class I objects \((t \sim 1-2 \times 10^5 \, \text{yr})\) are detectable for \(\lambda > 2\mu\)m and represent evolved protostars. Their SEDs have been successfully modelled in terms of a protostellar object surrounded by both a disk and diffuse circumstellar envelope\(^2\). The stellar core mass exceeds that of the surrounding circumstellar envelope and the majority of their luminosity stems from accretion. Class II objects \((t \sim 10^6 \, \text{yr})\) correspond to the classical T Tauri stars which are surrounded by an optically thick circumstellar disk for \(\lambda \leq 10\mu\)m. Their SEDs can be characterised by broadened blackbodies with circumstellar disks smaller than those of the Class I objects. Finally, Class III objects \((t \sim 10^7 \, \text{yr})\) represent the weak-lined, or naked T Tauri objects (Walter 1987) which lack the emission phenomena (H\(\alpha\) emission and metallic line emission) but are strong X-ray emitters. Their SEDs are comparable

\(^2\text{Class 0 protostars display spherical circumstellar dust envelopes only (and no disk emission).}\)
to a normal blackbody function with weak infrared excess, suggesting small amounts of circumstellar dust.

1.2 Outflows from Young Stellar Objects

From the theory of isolated star formation (Shu et al. 1987), a protostellar object forms via the accretion of mass from a large circumstellar envelope. It was of some surprise when observations showed young protostellar objects and T Tauri stars were loosing mass by ejecting gas along two narrow, oppositely directed jets. At first it was unknown how outflow fitted in with infall, but once it was realised that rotation of the parental cloud core causes material to spiral inward to add to the mass of the growing protostar, the core gains angular momentum from which a central protostar and flattened circumstellar disk are formed. Outflows provide a mechanism by which accreting protostars loose excess angular momentum. For the rest of this section, a brief introduction to the different components of outflows from protostars is presented. More detailed discussions can be found in Bachiller (1996), Cabrit, Raga & Gueth (1997), Reipurth & Raga (1999) and references therein.

1.2.1 Herbig-Haro Objects

During objective-prism and photographic surveys near the NGC 1999 region in Orion, Herbig (1950, 1951) and Haro (1952, 1953) noted the presence semi-stellar knots which emitted, among others, Balmer H$\alpha$, strong forbidden emission at $[\text{O}\,\text{i}]$ (6363Å), $[\text{O}\,\text{ii}]$ (3726/3729Å), $[\text{S}\,\text{ii}]$ (6717/6731Å), faint emission at $[\text{Fe}\,\text{ii}]$ (4244/4245Å), $[\text{O}\,\text{iii}]$ (4959/5006Å) and permitted emission at $\text{Ca\,ii}$ (4571Å). Herbig (1951) suggested these “blobs” were evidence of (1) faint blue, high-temperature stars or (2) an interaction of a late-type dwarf star with the surrounding nebular material. As these Herbig-Haro (HH) objects were located in the vicinity of dark clouds and the newly-discovered T Tauri stars (Joy 1942), they were thought to be related to the star formation process. From the detailed spectrophotometric analysis of HH objects, Böhm (1956), Osterbrock (1958) and Haro & Minkowski (1960) found that the forbidden-line emission takes place in regions where the average electron temperature and the mean electron density are $T_e \sim 10^4$ K and $n_e \sim 10^4$ cm$^{-3}$ respectively.
In order to isolate excitation mechanism(s) in HH objects, Strom, Grasdalen & Strom (1974) suggested HH objects were reflection nebulae illuminated by very young variable emission-line stars. Although this hypothesis was disputed by Schmidt & Miller (1979), Strom et al. (1974) found their selection of HH objects display radial velocities as high as \( \sim 150 \text{ km s}^{-1} \). Using proper motion data of HH 28/29 in the L1551 dark cloud, Cudworth & Herbig (1979) found that both objects have tangential velocities \( \sim 145 \text{ km s}^{-1} \). They suggested if the proper motion vectors of these objects were extended backwards, the projected lines pass very close to the position of L1551 IRS5, which is a deeply embedded protostar identified by Strom, Strom & Vrba (1976) and a possible point of origin for HH 28/29. In a series of papers on the proper motions of HH objects, Herbig & Jones (1981; 1983) and Jones & Herbig (1974; 1982), showed that HH objects displayed motions away from embedded sources. For the HH 1/2 system, they found the velocity vectors pointing away from the now accepted driving source HH 1/2 VLA1 (Pravdo et al. 1985; Rodríguez et al. 1990). By the early to mid 1980’s, it was generally accepted that HH objects were evidence of wind ejection taking place in the vicinity of young stellar objects.

A major step in characterising HH objects was provided by Schwartz (1978). By comparing the observed emission-line spectrum of HH 1 and the N49 supernova in the Large Magellanic Cloud, he proposed the emission could be produced by a supersonic wind ejected from a nearby young stellar object interacting with small ambient cloudlets. As the wind interacts with these cloudlets, a bow shock (facing the source) forms and the resulting radiating gas from this bow shock cools and emits the observable lines seen in HH objects. Since the shocked-cloudlet model of Schwartz, HH objects have been modelled as plane-parallel shocks (Dopita 1978; Raymond 1979; Hartigan, Morse & Raymond 1995) and bow shocks (Hartmann & Raymond 1984; Raga & Böhm 1987; Cantó & Raga 1998). The currently favoured model sees HH objects as “working surfaces”, where the jet-like flow interacts directly with the surrounding environment (Raga 1988; Blondin, Königl & Fryxell 1989; Raga & Cabrit 1993; Raga et al. 1993). Within the working surface, there are two shocks in operation: a bow shock which accelerates and excites ambient material and the Mach disk (jet shock) which decelerates jet material impinging on the ambient medium. High pressure gas exists between these two shocks and becomes ejected sideways and forms an envelope around the HH jet. As this envelope has a radius much larger than the radius of the jet beam, it presents a larger area to the surrounding ambient material which is entrained and seen as the CO outflow (see Raga & Cabrit 1993 and Raga et al. 1993 for more details).

\(^3\)In fact, the source is part of a binary system with the other component (HH 1/2 VLA2) driving HH 144, which is almost perpendicular to the HH 1/2 outflow (see Reipurth et al. 1993; et al. 2000.)
From the early photographic plates (Herbig 1974) and CCD imaging (Mundt & Fried 1983), it was apparent that HH objects display morphologies ranging from clumpy knots to highly-collimated jet-like structures emanating from T Tauri stars or low-luminosity embedded sources. Some of the most highly-collimated jets are found in HH 47 (Dopita, Evans & Schwartz 1982; see chapter 2, Figure 2.4), HH 34 (Reipurth et al. 1986; see chapter 2, Figure 2.2) and HH 111 (Reipurth, Raga & Heathcote 1992).

1.2.2 Near-Infrared H\textsubscript{2} (2.12\,µm) Outflows

Although HH objects and jets represent the optical component of outflows, there must also be unseen shocks occurring when outflows from extremely young protostars (such as Class 0 objects) interact with their parental molecular cloud. As the bulk of all molecular clouds are composed of molecular hydrogen (H\textsubscript{2}), do we see evidence of shock-excited emission? The first such evidence of shock-excited H\textsubscript{2} emission in a protostellar outflow was identified by Beckwith et al. (1978), who identified H\textsubscript{2} (2.12\,µm), ν = 1 → 0 S(1) emission associated with the HH nebulosity surrounding T Tau. Later, Elias (1980) detected H\textsubscript{2} emission associated with six HH objects and from line intensities, suggested that the H\textsubscript{2} emission arises from moderate-density (n \sim 10^4 \, cm^{-3}), shock-heated gas moving with velocities \sim 15 \, km \, s^{-1}. With the detection of H\textsubscript{2} in HH objects, it was unknown how both the optical and near-infrared emission could be associated with the same shocked region. As the optical spectra of HH objects usually require velocities \gg 40 \, km \, s^{-1}, it was expected that such velocities would dissociate any H\textsubscript{2}. For a number of HH flows, Zealey et al. (1986), Zinnecker et al. (1989) and Stapelfeldt et al. (1991) showed that the H\textsubscript{2}-emitting regions are usually located at (1) the wings of bow shocks which form at the working surfaces of the protostellar jet or (2) boundary layers where external molecular gas is entrained along the jet and/or at the outflow/cavity wall boundary\textsuperscript{4}. H\textsubscript{2} (2.12\,µm) emission arises in low-velocity (\sim 40-50 \, km \, s^{-1}) post-shock regions which are located in dense media (n \leq 10^6 \, cm^{-3}) with temperatures \sim 10^3 \, K. However, the exciting mechanism of H\textsubscript{2} in protostellar outflows is unknown, with continuous (C-type) and jump (J-type) shocks being used to describe line intensities (Smith 1993; 1994). For C-type shocks, a magnetised medium of low ionization is required to display a continuous change in shock properties within the shock structure. J-type shocks require high velocities which result in a jump in various parameters such as density, temperature and pressure. For this to occur, the medium must be of higher ionization.

\textsuperscript{4}See Figure 2.5 (chapter 2) which shows this in the HH 46/47 outflow.
and have a lower magnetic field strength than that seen in C-type shocks. In a number of HH flows, the H$_2$ emission has been modelled as either C-type (Ceph E; Eisloffel et al. 1996), J-type (HH 91; Gredel 1994), or both (HH 1; Noriega-Crespo & Garnavich 1994). For HH 7, it has been shown that the H$_2$ emission can be modelled in terms of C-type bow shocks and fluorescence (Fernandes & Brand 1995).

Recently, a number of protostellar outflows have been identified purely by their H$_2$ (2.12$\mu$m) emission. For example, the Class 0 protostar IC348 IR (McCaughrean, Rayner & Zinnecker 1994) drives a highly-collimated jet seen only in the infrared with faint outer bow-shocks seen on deep CCD images. The absence of optical HH lines such as H$_\alpha$ and [S$\text{II}$] can be explained if the outflow has not yet broken out of its parental molecular cloud. Similar to IC348 IR is IRAS00342+6347/HH 288 (McCaughrean 1997), which is associated with very faint HH emission at the most distant bow shocks. This suggests the flow is just beginning to break out of its parental molecular cloud.

1.2.3 Molecular CO outflows

With the introduction of millimetre-wave receivers in the 70’s, an important discovery was made when high-velocity carbon monoxide (CO) gas was discovered towards the Kleinmann-Low Infrared Nebula in Orion (Zuckerman et al. 1976; Kwan & Scoville 1976). When Snell, Loren & Plambeck (1980) mapped the L1551 region in Taurus, they found a double-lobed CO structure extending in opposite directions from the deeply embedded protostar, L1551 IRS5. This was the first detection of a molecular, bipolar outflow. They interpreted the CO lobes as dense shells of material swept up from a stellar wind originating from L1551 IRS5. Also located in the L1551 cloud are the objects HH 28/29 and HH 102$^5$ (Herbig 1974; Strom et al. 1974). Snell et al. (1980) found that all of these objects lie within the southwest (blue-shifted) CO lobe and suggested both HH objects and CO outflow may have a common origin$^6$.

To begin with, bipolar CO outflows were modelled in terms of molecular shells driven by wide-angled winds (Snell et al. 1980) or steady-state filled

\footnote{This is actually a large amorphous reflection nebula illuminated by L1551 IRS5.}

\footnote{Recent work by Devine, Reipurth & Bally (1999) suggests HH 28/29 are driven by L1551 NE which may also energize the southern part of the blue-shifted lobe of the L1551 outflow. Also, L1551 IRS5 is a binary which drives two distinct jets aimed towards HH 102 on the northern rim of the outflow cavity. Therefore, the blue-shifted lobe of the L1551 outflow is probably powered by several sources.}
flows with internal stratification (Levreault 1988a,b; Cabrit & Bertout 1990). As more young stellar objects were found associated with HH objects, jets and bipolar CO flows (e.g Bally & Lada 1983; Edwards & Snell 1983; 1984), the idea of “jet-driven” CO outflows became increasingly attractive. Masson & Chernin (1993) showed how optically-visible HH jets were able to drive CO outflows with bow shocks sweeping up ambient material and accelerating forward. The CO outflow is identified with this swept-up material. Although their model produces outflow cavities that are narrower than observed, they suggest a wandering jet can carve out a broad cavity. Raga & Cabrit (1993) proposed another model of CO outflows driven by highly-collimated jets. In their model, a bow shock compresses and sweeps up ambient material, which later re-expands into the cavity left behind and forms a turbulent wake identified as the CO outflow. As these bow shocks propagate further from the source, the decrease in cloud density causes them to expand and create widened cavities.

From ~ 200 known molecular CO outflows (i.e. Bally & Lada 1983; Fukui 1989; Wu, Huang & He 1996), their morphologies tend to display either poorly-collimated systems like L1551 IRS5 (Snell et al. 1980) and L43-RNO91 (Bence et al. 1998; see Figure 1.1c), or highly-collimated jet systems seen in L1448 (Bachiller et al. 1990), IRAS03282+3035 (Bachiller, Martin-Pintada & Planesas 1991) and HH 211 (Gueth & Guilloteau 1999; see Figure 1.1a). For the latter group, the higher degree of collimation is also seen in CO and/or SiO emission which is of extremely high-velocity (~ 100 km s$^{-1}$) and rather than being continuous, displays well-defined peaks (bullets) along the axis of the flow.

1.2.4 Radio Jets

The energy sources of outflows are usually detectable at centimetre wavelengths. In many instances, the emission is weak (~ mJy levels), compact and elongated. From computations of the spectral index$^7$, the emission from Class 0, Class I and Class II protostars is thermal free-free ($\alpha > -0.1$) with a small contribution from heated dust which dominates at millimetre and infrared wavelengths. Negative spectral indices are characteristic of non-thermal sources seen in more evolved objects, such as radio-emitting, weak-lined T Tauri stars (Class III objects). For cases where the emission is elongated, the major axis of the elongation corresponds with the axis seen in larger scale H$_2$, HH and/or CO outflows. These thermal jets appear within 10 AU of the exciting star (Anglada et al. 1998) and provide evidence of high

$^7$The spectral index, $\alpha$, is defined as $S_\nu \propto \nu^\alpha$. 
collimation even closer to the star than what is seen at optical and infrared wavelengths. In some cases, individual condensations within this distance of the driving source have been shown to move with velocities 600-1400 km s\(^{-1}\) (Martí, Rodríguez & Reipurth 1993; 1998). Thermal radio jets can be one-sided (VLA1623; Bontemps & André 1997), bipolar (HH 80/81; Martí et al. 1993; 1998) and even quadrupolar, in which case the system presumably contains two young stars (L723; Anglada, Rodríguez & Torrelles 1996, HH 111; Reipurth et al. 1999).

1.2.5 Source and Outflow Evolution

For Class 0 objects, the majority of known sources display highly collimated molecular H\(_2\)/CO outflows which suggests infall and outflow are occurring at the same time. An example of this class is HH 211-mm (McCaughrean et al. 1994; see Figure 1.1a). In Class I objects, outflow begins to dominate over infall and the outflow is usually detectable at optical (HH objects), near-infrared (shocks) and millimetre (bipolar CO lobes) wavelengths. An example of this class includes RNO 43-mm (Bence, Richer & Padman 1996, Eisöffel & Mundt 1997; see Figure 1.1b). By the time a source is in the Class II stage, outflow is nearing completion (i.e., L43-RNO 91 (Schild, Weir & Mathieu 1989, Bence et al. 1998; see Figure 1.1c) and at the Class III stage, outflow activity has stopped completely. An example of this class is the X-ray source HBC 647/ROX 47A (André & Montmerle 1994).

The most striking differences between outflows from Class 0-II sources can be seen if one look at the jets, collimation and presence/absence of shock-excited emission. For example, HH 211 displays a highly collimated jet, a wandering jet may be present in RNO 43 while L43-RNO 91 does not show any evidence of a jet. The collimation (i.e., length to width ratio) decreases from 10 in HH 211, 8 in RNO 43, and \(\sim 2\) in L43-RNO 91. There is also a progressive decline in base cavity opening angles, with \(\theta_c \sim 30^\circ\) in HH 211 and \(\theta_c > 90^\circ\) in L43-RNO 91. As to the presence/absence of shock-excited emission, HH 211 displays only shock-excited H\(_2\) emission, RNO 43 contains co-existent HH/H\(_2\) emission along the entire flow, while L43-RNO 91 shows no evidence of HH emission but faint and extended H\(_2\) emission has been identified near the outflow source (Kumar, Anandarao & Davis 1999). The presence of strong H\(_2\) emission in HH 211 and lack of strong HH and/or H\(_2\) emission in the L43-RNO 43 outflow supports the idea that outflow strength declines with increasing source age (i.e., Bontemps et al. 1996; Saraceno et al. 1996).
Figure 1.1: Examples of Class 0, I and II protostellar objects. **left:** Class 0: HH 211. The top panel shows low-velocity CO emission outlining the cavity, whereas the lower panel shows high-velocity CO emission traces a highly collimated jet. The grey-scale emission is from shock-excited H$_2$ emission (from Gueth & Guilloteau 1999). **middle:** Class I: RNO 43. Position of HH objects (white markers) overlaid on the $^{12}$CO emission. Both the optical and CO emission display a “wandering” (from Bence et al. 1996). **right:** Class II: L43-RNO 91. $^{12}$CO emission outlines a wide limb-brightened cavity. No HH, but faint H$_2$ emission is seen in this flow (from Bence et al. 1998).
1.3 Giant Herbig-Haro Outflows

Prior to 1994, it was generally believed that the extent of HH outflows was \( \sim 0.3 \) pc for regions such as Orion \((D \sim 470 \) pc\). It is interesting that the inferred sizes of these outflows was typically the same as the field-of-view of most optical CCD detectors of the time. Although larger \( (> 1 \) pc\) flows such as R Mon/HH 39 (Herbig 1968), RNO 43 (Ray 1987), Z CMa/HH 160\(^8\) (Poetzel, Mundt & Ray 1989) and HH 80/81 (Martí et al. 1993) were known, their lengths were generally attributed to the higher luminosity of the driving source \( (\sim 10^{3-4} L_\odot) \). Bally & Devine (1994) were the first to question the true length of outflows from low-luminosity sources by suggesting that the well-known HH 34 outflow in the L1641 (Orion A) molecular cloud was not \( \sim 0.3 \) pc in length, but in fact \( \sim 3 \) pc!

To the north of the driving source (HH 34IRS), there is a string of HH objects\(^9\) for which many optical, near-infrared and far-infrared surveys have failed to detect plausible energy sources. Likewise, another chain of known HH objects\(^{10}\) are found to the south of HH 34IRS. Like the northern group, no energy source had been found for these objects. Existing velocity information on HH 33/40 to the north of HH 34IRS suggests these objects have radial motions \( V_{lsr} \sim 70-130 \) km s\(^{-1}\), which is similar in magnitude but opposite in direction to the velocities seen in the blue-shifted HH 34 jet and HH 34S. With this information, they suggested that the northern string of objects lie in the red-shifted lobe, while those to the south of HH 34IRS lie in the blue-shifted lobe. Finally, from a \(^{13}\)CO integrated intensity map of the region, they found large-scale cavities symmetrically placed about \( 8' \) to the north and south of HH 34IRS. Each cavity coincides with the northern (HH 33/40) and southern (HH 86-88) terminal bow shocks of the suggested giant HH flow.

Using deep red Schmidt plates, Ogura (1995) proposed that the known HH 1/2 (Orion A; L1641) and HH 124 (NGC 2264) outflows were in fact associated with flows of lengths 5.9 pc and 5.4 pc respectively. Another hint that low-mass sources drive parsec-scale flows was shown when Bence et al. (1996) identified a 5 pc CO outflow associated with the Class 0/I source RNO 43-mm\(^{11}\). With the confirmation that HH 34 is indeed part of a 3 pc flow (Devine et al. 1997), Eislöeffel & Mundt (1997) and Reipurth, Bally &

\(^8\) See chapter 5.

\(^9\) With decreasing distance from HH 34IRS: HH 33, HH 40, HH 85, HH 126 and HH 34N.

\(^{10}\) With increasing distance from HH 34IRS: HH 34 jet, HH 34S, HH 34X, HH 173 and HH 86-88.

\(^{11}\) RNO 43-mm also drives a 3.4 pc HH flow consisting of HH 179 and HH 243-245. See Eislöeffel & Mundt (1997) and Reipurth et al. (1997).
Devine (1997; hereafter RBD97) each conducted a CCD imaging survey of known HH flows to determine if they extended over parsec-scale distances. RBD97 identified HH 111/113/311 as the largest at a staggering projected length of 7.7 pc! All of the above surveys found that the true extent of HH flows may have been underestimated by factors as high as ten. Since 1997, increases in the field of view afforded by CCD detectors (> 20-30') have led to the discovery of roughly 2-3 dozen giant HH flows associated with low-mass young stellar objects.

### 1.3.1 Implications of Giant Herbig-Haro Flows

Eisloeffel & Mundt (1997) and RBD97 discuss the implications of giant outflows from low-mass stars, but the most important was the realisation that HH flows were now able to drive molecular CO outflows associated with the same source. Prior to the discovery of giant HH flows, mass-loss estimates from optical HH jets showed typical values between $10^{-6} - 10^{-8} \ M_\odot \ yr^{-1}$ (Mundt, Brugel & Bürke 1987). These figures were up to 10-100 times lower than typical mass-loss rates estimated from CO observations. From a historical perspective, the discrepancy is probably related to the intrinsic difficulty in measuring the neutral component of HH jets (see Bacciotti & Eisloeffel 1999 and references therein). For a jet of radius 1'' with $n_e = 100$ cm$^{-3}$ and velocity = 300 km s$^{-1}$, $\dot{M} \geq 2 \times 10^{-7} / x_e \ M_\odot \ yr^{-1}$ where $x_e$ is the ionization fraction. In a spectroscopic survey of HH jets, Bacciotti & Eisloeffel (1999) presented a model-independent method for determining $x_e$. In most cases, they found $x_e \leq 0.1$, which implies $\dot{M} \geq 2 \times 10^{-6} \ M_\odot \ yr^{-1}$. The resulting decrease in $x_e$ implies higher mass-loss rates comparable to the associated CO outflows.

As mentioned in Eisloeffel & Mundt (1997) and RBD97, the increased length of HH flows beyond 1 pc yields dynamical ages $\tau_{dyn} \sim 10^4 \ d_{pc}/v$ where $d_{pc}$ is the projected distance in pc and $v$ represents the highest observed velocity in terms of 100 km s$^{-1}$. For giant HH flows, $\tau_{dyn}$ is up to 10 times larger than previously found and once this is factored in, the total momentum of HH jets ($0.5-10 \ M_\odot \ km \ s^{-1}$) is comparable with the total momentum in a number of CO outflows ($1-20 \ M_\odot \ km \ s^{-1}$; Cabrit & Bertout 1992).

With increased projected lengths and accurate measurements of the optical flow mass, it appears that HH jets are indeed capable of driving molecular CO outflows.

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12See Mundt et al. (1987).
1.4 Aims of this Thesis

As the number of known giant HH flows increases, a natural question to ask is what percentage of known and newly detected HH flows extend out to parsec-scale lengths? With well over 450 known HH objects (Reipurth 1999), it is quite plausible that some are in fact associated with known HH flows as nearly 50% of objects have yet to be associated with an energy source. With the identification of large-scale CO cavities at the terminal working surfaces, the HH 34 outflow may have dire consequences for the future evolution of the L1641 molecular cloud. What are the consequences of these cavities in terms of the molecular cloud being able to continue forming stars?

This thesis attempts to answer the above questions by conducting a wide-field survey of star forming regions to (a) identify new giant HH flows and (b) characterise their effect on their parental molecular clouds.

The format of this thesis is as follows: As giant HH flows tend to extend up to several degrees on the sky, chapter 2 presents ESO/SERC Southern Sky Atlas material of known HH flows to determine if wide-field (6°×6°) Schmidt plates are capable of characterising outflows in general and identifying giant HH flows. Chapter 3 presents a multi-wavelength (ESO/SERC, CCD narrow and broad-band optical imaging, IRAS) study of known HH objects which have yet to have an energy source positively identified and determine if they are part of giant HH flows. Chapter 4 presents results of a search for giant HH flows using wide field-of-view (4°×4°) material from the new Anglo-Australian (AAO) and United Kingdom Schmidt Telescope (UKST) Hα survey of the Southern Galactic Plane. This chapter combines the methods and techniques developed in the previous two chapters to identify giant HH flows and characterise their effect on the L1630 and L1641 giant molecular clouds in Orion. Initial results of an AAO/UKST Hα survey for giant HH flows in the Canis Major region are presented in chapter 5. Finally, chapter 6 concludes with a summary of the major findings of this thesis.