

# THE STAR FORMATION NEWSLETTER

*An electronic publication dedicated to early stellar evolution and molecular clouds*

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## *From the Editor*

The Star Formation Newsletter has now existed for a bit longer than a year. During that time the number of subscribers, distributed all over the world, has climbed to almost 500, including a number of libraries, and it continues to steadily increase. From this and from the many positive and encouraging e-mails I have received I gather that the original goal of the Newsletter, namely to act as a rapid courier of scientific news within the star formation community, has been largely fulfilled. Consequently I have decided to continue with the publication of the Newsletter beyond this trial period.

The Star Formation Newsletter is the product of a common effort of all of its readers. By sending in the abstracts of your newly accepted papers your results become rapidly known throughout the community, just as you get to know about everybody else's latest works. It is my hope that the Newsletter can reach a 90% completeness in its coverage of the new literature. I estimate that at present at most two thirds of abstracts of papers on low mass star formation and molecular clouds appear in the Newsletter. You can help to increase this percentage in two ways: by sending your abstracts and by encouraging your colleagues working in the field to receive and contribute to the Newsletter.

Other features of the Newsletter include the abstracts of recent Ph.D. theses, information on meetings, new jobs, new books, and short notes where you can make announcements or inquiries to the community.

From now on all issues of the Newsletter are available through anonymous ftp thanks to Fionn Murtagh of ESO, who every month makes a WAIS index of each new issue. Using WAIS you can search through all abstracts for subjects of your interest and retrieve the corresponding issue, if you do not already have it. See the last page for instructions.

## *Abstracts of recently accepted papers*

### **A Radio Candidate for the Exciting Source of the L1287 Bipolar Outflow**

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The FU Orionis phenomenon has been proposed to account for the bipolar molecular outflows commonly observed in star forming regions. Perhaps the best case in support of this hypothesis is the L1287 outflow, recently suggested to be excited by a visible binary FU Ori system (RNO 1B/1C). However, a different object has also been proposed to excite the powerful bipolar molecular outflow in L1287: a yet undetected deeply embedded source, inferred from polarimetric studies of the region and displaced several arc sec from the FU Orionis system. Sensitive 3.6-cm Very Large Array observations of the region reveal the presence of a radio continuum source coincident within 1'' with the predicted position of the embedded source and with the catalog position of IRAS 00338+6312. This radio continuum source has positive spectral index and presents evidence of elongation approximately along the axis of the bipolar outflow. These two properties are characteristic of other thermal radio jets known to be associated with the exciting source of bipolar outflows. We propose that this radio continuum source is the most plausible candidate to excite the L1287 outflow and that the relation of the visible FU Orionis system with the outflow is unclear.

Accepted by The Astrophysical Journal (Letters)

# Momentum Transfer By Astrophysical Jets

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We have used three dimensional smoothed particle hydrodynamical simulations to study the basic physical properties of the outflow that is created by a protostellar jet in a dense molecular cloud. The dynamics of the jet/cloud interaction is strongly affected by the cooling in the shocked gas behind the bow shock at the head of the jet. We show that this cooling is very rapid, with the cooling distance of the gas much less than the jet radius. Thus, although ambient gas is initially driven away from the jet axis by the high thermal pressure of the post-shock gas, rapid cooling reduces the pressure and the outflow subsequently evolves in a momentum-conserving snowplow fashion. The velocity of the ambient gas is high in the vicinity of the jet head, but decreases rapidly as more material is swept up. Thus, this type of outflow produces extremely high velocity clumps of post shock gas which resemble the features seen in outflows.

We have investigated the transfer of momentum from the jet to the ambient medium as a function of the jet parameters. We show that a low Mach number ( $\leq 6$ ) jet slows down rapidly because it entrains ambient material along its sides. On the other hand, the beam of a high Mach number jet is separated from the ambient gas by a low density cocoon of post-shock gas, and this jet transfers momentum to the ambient medium principally at the bow shock. In high Mach number jets, as those from young stellar objects, the dominant interaction is therefore at the bow shock at the head of the jet.

Accepted by the Astrophysical Journal.

# Proper motion measurements and high resolution imaging of the HH 46/47 outflow

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We have carried out a detailed study of the proper motions of the knots in the HH 46/47 jet and counterjet, as well as of the condensations in the associated bow shocks HH 47C and HH 47D. In the jet the tangential velocities are about  $200 \text{ km s}^{-1}$  with marked variations of about  $\pm 100 \text{ km s}^{-1}$ . In the other parts of the jet system the average tangential velocities are somewhat lower at  $70 - 170 \text{ km s}^{-1}$ . Given reasonable assumptions about the pattern speed at the apex of the presumed bow shock HH 47A, the orientation angle of the HH 46/47 outflow with respect to the plane of the sky is found to be  $34^\circ \pm 3^\circ$ . This enables us to correct the observed radial and tangential velocities in the jet for projection effects allowing the local flow speed of the jet and the knot pattern speed to be derived. A typical flow speed of about  $300 \text{ km s}^{-1}$  is found in the jet. Along part of the jet the knots at its northeastern edge are clearly moving at a lower velocity than knots closer to the jet axis. The ratio  $\zeta$  between the pattern speed of the knots and the flow speed of the jet appears to show distinct phases. The components of lower tangential velocity and eventually also of lower pattern speed may be created by entrainment of the ambient material into the jet along parts of the jet channel.

We coadded images taken under excellent seeing conditions into a single high-signal/noise image and deconvolved the latter using the Richardson-Lucy algorithm. The deconvolved image has a seeing of  $0.''47$  (FWHM) and contains a wealth of structural detail. The jet clearly shows several kinks and, most important, along most of its length consists of two well-separated bright rims. We discuss this unusual limb-brightening effect, which has only been seen in a limited number of jets so far.

Proper motions were also measured for the condensations in the arc-shaped HH-objects HH 47D and HH 47C, which are assumed to be the bow shocks of the jet and the counterjet, respectively. The internal pattern of motion of these condensations is in good agreement with predictions from simple bow shock models.

Accepted by Astron. Astrophys.

# The Collimation of Jets and Bipolar Outflows in Young Stellar Objects: Inertial Confinement

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We describe an effective mechanism for collimating the outflow from a YSO. Our study is based on a series of numerical simulations of the interaction of a central, isotropic wind with a toroidal circumstellar accretion flow. A bipolar shock configuration is quickly established as a consequence of the decrease of the accretion flow density from equator to pole. The jet is collimated through the inertial confinement mechanism (Icke *et. al.* 1992). A prolate inner shock focuses the wind toward the axis forming the jet. At the same time the contact discontinuity at the equator becomes unstable and is dragged by the jet into a chimney. This chimney confines the high-velocity gas and maintains the collimation. The kinematical pattern of the outflow is consistent with the observations.

Accepted by Astron. & Astrophys.

# Detection of the Carbon Monoxide Ion ( $\text{CO}^+$ ) in the Interstellar Medium and a Planetary Nebula

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We report detection of the carbon monoxide ion ( $\text{CO}^+$ ) in the interstellar medium (M17SW) and a planetary nebula (NGC 7027). These detections are based on observations of three millimeter and submillimeter transitions in M17SW and one in NGC 7027. Chemical models suggest that  $\text{CO}^+$  should be most abundant where complex molecules are least likely to be present. In our search for  $\text{CO}^+$  we therefore minimized the chance of confusion while maximizing the probability of detection by observing regions whose chemistry is dominated by the effects of ultraviolet radiation.

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# A Protostellar Jet Model for the Water Masers in W49N

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Observations by Gwinn, Moran, & Reid of the proper motions of water masers in W49N show that they have an elongated distribution expanding from a common center. Features with high space velocity only occur far from the center, while low-velocity features occur at all distances. We propose that these observations can be interpreted in terms of a shell of shocked molecular gas that is driven by the expanding cocoon of a high-velocity protostellar jet. We present 3D numerical simulations in support of this interpretation and argue that this source provides a unique opportunity for a detailed study of jet-driven cocoons.

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# The Circumstellar Environment of the FU Orionis Pre-Outburst Candidate V1331 Cygni

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High resolution ( $\sim 4''$ ) aperture synthesis maps of the CO (1 $\rightarrow$ 0), <sup>13</sup>CO. (1 $\rightarrow$ 0), <sup>13</sup>CO. (2 $\rightarrow$ 1), and associated continuum emission from the FU Orionis candidate V1331 Cygni reveal a massive,  $0.5 \pm 0.15 M_{\odot}$ , circumstellar disk surrounded by a flattened gaseous envelope,  $6000 \times 4400$  AU in size, mass  $\geq 0.32 M_{\odot}$ . These images and lower resolution measurements also trace a bipolar outflow and gaseous ring,  $4.1$  by  $2.8 \times 10^4$  AU, mass  $\geq 0.07 M_{\odot}$ , radially expanding at  $22 \pm 4$  km/s. We suggest this ring is a swept-up gaseous torus from an energetic mass ejection stage, possibly an FU Orionis outburst or outbursts,  $\sim 4 \times 10^3$  years ago that imparted  $\geq 10^{45}$  ergs into the ambient cloud.

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## Statistical Analysis of Turbulence in Molecular Clouds

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We present an investigation of the statistical properties of fluctuating gas motions in five nearby molecular clouds using the two-point autocorrelation and structure functions and the power spectra of their radial velocity structure as traced by emission-line centroid velocities. Our analysis includes observations made with the AT&T Bell Laboratories 7-meter Crawford Hill antenna (1.1' beamwidth) of <sup>13</sup>CO  $J = 1 \rightarrow 0$  emission in OrionB, MonR2, L1228, and L1551 and also <sup>13</sup>CO  $J = 2 \rightarrow 1$  observations of the molecular gas surrounding the Herbig-Haro object HH83 lying just west of L1641 in the OrionA cloud which were obtained with a higher spatial resolution (0.22') using the IRAM-30m telescope on Pico Veleta, Spain (Bally et al. 1994). The effects of beam smoothing and the interpolation of a set of observations onto a regular spatial grid are studied using model spectral line data cubes and we find that the behavior of the statistical functions presented here and those presented elsewhere by other authors are heavily influenced by these effects at scales comparable to and somewhat larger than the beamwidth. At larger lags real correlations are detected and we use the e-folding length of the autocorrelation function (i.e. the correlation length) to investigate the characteristic scales of the underlying turbulent flow. We find that this measure is dependent on the range of scales sampled by the observations themselves both for our data and for previously existing observations presented by other authors and we interpret this result and the observed similarity between the functional forms of the statistical functions derived for different data sets as evidence for a self-similar turbulent hierarchy of gas motions extending over a wide range of scales in the interstellar medium. Power law fits to the observed structure functions yield a mean index describing the hierarchy of  $0.86 \pm 0.3$ , which translates into a velocity dispersion - region size relationship of the type first introduced by Larson (1981),  $\Delta V \propto l^{\gamma}$ , with  $\gamma = 0.43 \pm 0.15$ . This result is consistent with that found by Larson in his original analysis,  $\gamma \approx 0.38$ , and with the range found in more recent studies,  $0.35 < \gamma < 0.7$  (e.g. Myers 1987). We also discuss the observed scaling laws in relation to the predictions of phenomenological theories of forced, isotropic turbulence. The mean turbulent stress and maximum energy transport rate as a function of scale are obtained from the velocity power spectra following the procedure of Kleiner & Dickman (1987), and the results are discussed in the context of scale-dependent star formation and the generation of turbulence in molecular clouds.

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# Radio Continuum, Ammonia and Water Maser Observations of Bright, Unassociated IRAS Point Sources

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We present matching-beam 6 and 2-cm radio continuum observations made with the Very Large Array, and ammonia and water maser observations made at the Haystack Observatory of 12 IRAS point sources selected from the survey of Scalise et al. (1989) of bright, unassociated IRAS point sources. These sources have 60 or 100  $\mu\text{m}$  flux densities in excess of  $10^3$  Jy and have no previous reference in any of the 37 catalogs considered for association of IRAS sources with known sources. Six of the twelve sources have associated radio continuum, ammonia and water maser emission and all of them show at least one of these three emissions. In all sources detected, the ammonia is warm ( $T \sim 20$  K) and suggests the association of dense molecular gas with embedded heating sources. It is argued that all sources in the sample could be associated with time-variable  $\text{H}_2\text{O}$  maser emission. The radio and far-infrared data appear to indicate that these sources are star-forming regions, powered by a late O or early B-type star. Several of the sources of lower luminosity ( $\sim 5 \times 10^3 L_\odot$ ) appear to have ionizing photon fluxes *in excess* of those expected for a ZAMS star. Possible explanations for this discrepancy are discussed.

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# Fabry-Perot Observations and New Models of the HH 47A and HH 47D Bow Shocks

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We present new models for the HH 47A and HH 47D bow shocks based on line flux and velocity maps obtained with an imaging Fabry-Perot spectrometer. We confirm that HH 47A and HH 47D each show a bow shock/Mach disk morphology, and that velocity variability in the outflow can account for the observed structures. While it was suggested a decade ago that the inner working surface HH 47A appears to be traveling into the wake of HH 47D, we find kinematic evidence that the outer bow shock HH 47D is also not the primary ejection event in the outflow but follows in the wake of previously ejected material. By comparing the observed line ratios and line profiles to those predicted by our bow shock models, we find that both bow shocks have substantially lower shock velocities than their space motions would imply, and that the emission from each bow shock is systematically blueshifted from the rest-frame velocity of the ambient emission, indicating a co-moving preshock medium. We derive kinematic ages of  $\sim 1150$  yr for HH 47D and  $\sim 550$  yr for HH 47A, which implies that the stellar driving source may undergo repetitive eruptions similar to FU Ori-type outbursts every several hundred years. This timescale is similar to estimates made by Reipurth and collaborators for the separation between major outbursts in the HH 34 and HH 111 stellar jets.

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## W134: A New Pre-Main Sequence Double-Lined Spectroscopic Binary

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We report the discovery that the pre-main sequence star Walker 134 in the young cluster NGC 2264 is a double-lined spectroscopic binary. Both components are G stars with strong Li I 6708 Å absorption lines. Twenty radial velocity measurements have been used to determine the orbital elements of this system. The orbit has a period of  $6.3532 \pm 0.0012$  days and is circular within the limits of our velocity resolution;  $e < 0.01$ . The total system mass is  $M \sin^3 i = 3.16 M_{\odot}$  with a mass ratio of 1.04. Estimates for the orbit inclination angle and stellar radii place the system near the threshold for eclipse observability; however, no decrease in brightness was seen during two attempts at photometric monitoring. The circular orbit of W134 fills an important gap in the period distribution of pre-main sequence binaries and thereby constrains the effectiveness of tidal orbital circularization during the pre-main sequence.

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## A Catalog of Bright-Rimmed Clouds with IRAS Point Sources: Candidates for Star Formation by Radiation-Driven Implosion. II. the Southern Hemisphere

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Forty-five bright-rimmed clouds associated with IRAS point sources have been selected in the southern hemisphere from the ESO (R) Atlas in addition to the 44 objects of the northern work (Paper I; Sugitani et al. 1991, ApJS 77, 59). Again they are good candidates for the sites of star formation induced by radiation-driven implosion. Four of them are known to be associated with HH objects, and three with molecular outflows. Most of their sizes are less than 1 pc, and the luminosities of the associated IRAS sources, 20 to  $3 \times 10^4 L_{\odot}$ , are much larger than those of the IRAS sources associated with Bok globules or dense cores in dark cloud complexes, both having a similar mass range. This suggests that intermediate mass stars or multiple star systems are mainly formed in the bright-rimmed clouds. IRAS luminosity to cloud mass ratios are significantly greater than those in Bok globules or dense cores. The results confirm most of the findings of Paper I.

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## CS Multitransitional Study of Density Distribution in Star Forming Regions II: The S140 Region

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The S140 molecular cloud was observed in 5 transitions of CS with resolutions of  $11''$ – $45''$ . The data were analyzed with both the LVG and microturbulent models of radiative transfer to derive the density structure. It was found that the CS emission comes from three components of gas: a spherical component centered on the infrared cluster, an arc component along the ionization front between the S140 HII region and the dense molecular cloud core, and a high-velocity component from the dense part of a molecular outflow. The spherical component contributes most to the CS emission and was analyzed in more detail than the other components. Using a temperature distribution derived from an analysis of the dust emission from S140, we fit a power-law density distribution of  $n(r) = n_i(r/r_i)^{-\alpha}$

to the spherical component. The best fit was for  $n_i = 1.4 \times 10^6$  (density at  $r_i = 0.026$  pc) and  $\alpha = 0.8$ . The density ( $n_i$ ) was found to be greater than or equal to the density required to account for the dust emission, depending on the dust opacity laws adopted. The presence of optical emission (Dinerstein et al. 1979) suggests a clumpy structure for the dense gas. Considerations of the virial mass and the lowest amount of column density required to produce dust emission put the volume filling factor ( $f_v$ ) of the dense gas at  $\sim 0.14$ – $0.5$ .

We compared S140 with other regions of star formation where the density structure has been derived from excitation analysis. Source-to-source variations in density gradients and clumpiness clearly exist, ranging from  $\alpha = 2$  and  $f_v \sim 1$  in B335 to  $\alpha \sim 0$ ,  $f_v \sim 0.1$  in M17. There is a tendency for more massive star forming regions to have a flatter density distribution, a more clumpy structure, and a larger number of young stars. The implications of this tendency are discussed.

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*Dissertation Abstracts*

**Near-Infrared spectroscopy of shocked molecular hydrogen in star formation regions**

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Ph.D degree awarded: November 1993

The work presented in this thesis is devoted to the study of the physics of shock waves in dense molecular cloud environments that are typical of star forming regions. The structure of these shock waves are analysed in terms of the two basic models: J-shock and C-shock.

We have investigated the H<sub>2</sub> emission properties from Herbig-Haro 7 and the DR 21 bipolar outflow by measuring several spectral lines arising in the K band. These H<sub>2</sub> lines cover a wide range in energy of the upper level (6000-25000 K) and enables a detailed study of the temperature distribution of the gas. The calculated column density ratios have been compared to J and C-shock models for different shock geometries. We have shown that current oblique J- and C-shock models fail to explain the observed H<sub>2</sub> column density ratios. J-shock models fail to provide sufficient hot gas from behind the shock front and are not able to explain the large line intensities observed in the high-vibrational H<sub>2</sub> lines. The line emission from the 6 positions observed within the HH 7 bow are shown to be consistent with a paraboloidal bow shock geometry, which however necessitates of an extra source of excitation of the high energy levels to explain the H<sub>2</sub> line ratios. We present a study of the effects of the UV radiation field associated with the bow shock structure and show that a shock-induced Far-UV radiation field with a strength of  $G_0 = 10^2 - 10^3$ , can account for the observed H<sub>2</sub> line ratios. We suggest that shocks are responsible for the low-lying level excitation of the H<sub>2</sub> molecule while Ly $\alpha$  resonance pumping is responsible for the high-excitation line emission.

Measurements of several infrared emission lines of H<sub>2</sub> in the K window from the DR 21 bipolar outflow, show different excitation conditions for the East and West lobes of H<sub>2</sub> emission. The higher H<sub>2</sub> line ratios measured for the East lobe is indicative of enhanced excitation for the high-excitation levels of the H<sub>2</sub> molecule, which can be caused by either shock-produced Ly $\alpha$  resonance pumping or by direct UV excitation of H<sub>2</sub> from the central HII region and producing higher fluorescent fluxes. We show that the H<sub>2</sub> emission can be explained in terms of a model consisting of a C-shock and a PDR. The H<sub>2</sub> line ratios are best fitted with a PDR model with parameters: FUV field in the range  $10^2 \leq G_0 \leq 10^3$  and densities  $n \geq 3 \times 10^3 \text{ cm}^{-3}$ .

We show that the H<sub>2</sub> fluorescent emission from both HH 7 and DR 21 is reproduced better with an ortho-to-para ratio of 1.8.