Signposts of Low Mass Star Formation in Molecular Clouds

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Regions of massive star formation are easily recognizable because of the presence of bright, often very extended H II regions. The more quiescent places where only low mass star formation takes place are not so immediately obvious to identify. Most of the low mass star forming regions known today were found in the 1950's, mainly through objective prism surveys for Hα emission stars done by Joy, Herbig, Haro and others. Their results are summarized and supplemented by later findings in a new catalogue by Herbig and Bell (1988), which lists 742 mainly low mass pre-main-sequence stars. Another recent and rich source of low mass young stars is the IRAS catalogue. IRAS data towards clouds, however, often suffer from source confusion and, in particular, extraction problems because of background emission.

Reflection and Emission Nebulae

The youngest and generally most interesting stars are still intimately associated with their placental material, and therefore often show small, faint reflection nebulae. In the earliest evolutionary stages a star is normally not visible at all, but through cavities blown open to the cloud surface it may illuminate the surrounding cloud. Perhaps the finest known case is the Re 50 nebula in Orion, shown in a CCD image through a red broadband filter in Figure 1. This object was found by inspection of deep red Schmidt plates of the L 1641 molecular cloud in Orion (Reipurth 1985). The northern elongated nebula is a beam of light that escapes from a 250 $L_{\odot}$ embedded infrared source. The southern nebula is a molecular cloud clump which is illuminated by the same star through a channel hidden from view. The whole object is highly variable, to the extent that it looks different each time it has been observed during the last 6 years. Moreover, inspection of older Palomar Schmidt plates from 1955 shows nothing of the nebula. Perhaps we are here for the first time witnessing the emergence of a young star from its cloud-enshrouded birthplace (Reipurth and Bally 1986, Scarrot and Wolstencroft 1988). Some other similar reflection nebulae, apparently in slightly more evolved stages, are the PV Cep, Re 5 and IRN nebulae (Cohen et al. 1977, Graham 1986, Schwartz and Henize 1983).

After a young star has broken through its cloud cover to the outside world it passes through phases where strong outflowing winds create shocks in the ambient medium, the so-called Herbig-Haro objects. These are normally found as chains of small nebulae stretching away from an infrared source. They can be identified by their very characteristic emission line spectra. In recent years it has become clear that a subset of the Herbig-Haro objects take the form of highly collimated jets, remarkably similar in appearance to the jets from extragalactic radio sources (for a recent review, see Mundt 1988).

One of the finest jets known to be associated with a young star is the HH 34 jet. It was originally noted on a deep red Schmidt plate, and subsequent CCD imaging revealed its extraordinary nature (Reipurth 1985, Reipurth et al. 1986). Figure 2 shows an almost 30 arcsecond long jet emerging from a faint emission line star, and pointing right towards HH 34 in the lower part of the image. We are here witnessing mass loss from the star ejected in a collimated supersonic beam, ending in a bow shock where the outflowing material rams into the ambient medium. A comparison between the original discovery image from 1982 with a series of identical images taken up to 1989 shows that the shock structures seen as knots in the jet have a proper motion in the direction away from the source. A second oppositely oriented bow shock was found on the other side of the jet by Bührke et al. (1988), demonstrating that the outflow is bipolar. Studies of such objects provide key information on the earliest phases of stellar evolution.

Given the success of the initial examinations of Schmidt plates in identifying new and unusual regions of low mass star formation, a more ambitious project was initiated.

A Survey of Molecular Clouds with the ESO Schmidt Telescope

Because of their large field, Schmidt plates are ideal for surveys. The fine-grained IIIa-F plates are, when properly hypersensitized, particularly useful for searches for the often intrinsically red and heavily obscured small reflection nebulae, as well as for Herbig-Haro objects, since their emission lines mainly fall within the spectral sensitivity curve of the IIIa-F emulsion. Using the ESO 1-m Schmidt telescope at La Silla, Chile, equipped with a RG 630 filter, a large scale survey of molecular clouds all along the southern galactic plane has been carried out during the last two years. All plates were taken by H.-E. Schuster, Guido Pizarro and Oscar Pizarro. More than two hundred tiny nebulae in dark clouds have been identified.

Seen on deep Schmidt plates, exposed to their best S/N ratio, such small nebulae appear to be superimposed on a background of relatively high density. Thus at times it is difficult to recognize the tiny objects by merely visually inspecting the plates. The well known photographic technique of diffuse-light amplification brings remedy to the problem by "removing" the chemical fog contributing to the high overall density, and by increasing the contrast of the image at the density level required. However, as such nebulae are sometimes found in regions with nearby OB stars surrounded by bright H II regions, there can be large density variations over the photographic plate. Therefore, pure amplification will effectively obscure as much as it reveals, due to the very limited dynamic range which this process offers. Consequently it is often necessary to employ a strong unsharp mask during the amplification process. The technique of unsharp masking has been described elsewhere and shall not be dealt with here. Serving as an analogue low frequency filter, the mask brings down the overall contrast of (a larger part of) the plate to a level which allows for contrast amplification of the whole area under study.

The follow-up Observations

In order to separate reflection from emission nebulae, one should ideally obtain a spectrum of each nebula. However, most of these tiny objects are so faint that it would require immense amounts of observing time on large telescopes to complete such a programme. But another simple and fast technique exists. For each object direct CCD images were obtained at the Danish 1.5-m telescope at La Silla, one through a far-red broadband Gunn z filter extending to the CCD cutoff beyond 1 micron, and one through a narrow-band interference filter centred on the [SII] 6717/6731 emission lines. A reflection nebula associated with a partly embedded young low-mass star is very red and will show up prominently in the broadband Gunn z filter, but rarely in the narrow-band sulphur filter. On the other hand, Herbig-Haro objects are strong emitters in the 6717/6731 lines, but have no

Figure 1: *A Gunn r filter CCD image taken 4 March 1986 at the Danish 1.5-m telescope. An infrared source is hidden above the upper nebula, which is a beam of light escaping from the newborn star. The lower nebula is a molecular cloud clump illuminated by the embedded star.*

Figure 2: *A [S II] filter CCD image taken at the Danish 1.5-m telescope of the HH 34 region. Here a shocked emission line jet flows supersonically away from a faint young star. The jet cools to invisibility, but continues and eventually rams into the ambient medium in a bow shock.*

strong lines in the Gunn z bandpass and virtually no continuum, so they will show up very bright in the narrow-band sulphur filter, and barely, if at all, in the Gunn z filter. In this way the number of known Herbig-Haro objects have been doubled. Since such objects have most of their emission concentrated in a couple of strong emission lines, it is feasible to study spectroscopically this subset of the list of new small nebulae. These additional observations are important for final confirmation, since distant H II regions sometimes can mimic HH objects. But the gradual build-up of experience helps: at the beginning of the survey only 15 % of the objects which on the plate looked to be Herbig-Haro objects were actually confirmed as such, while at the end the rate exceeded 90 %.

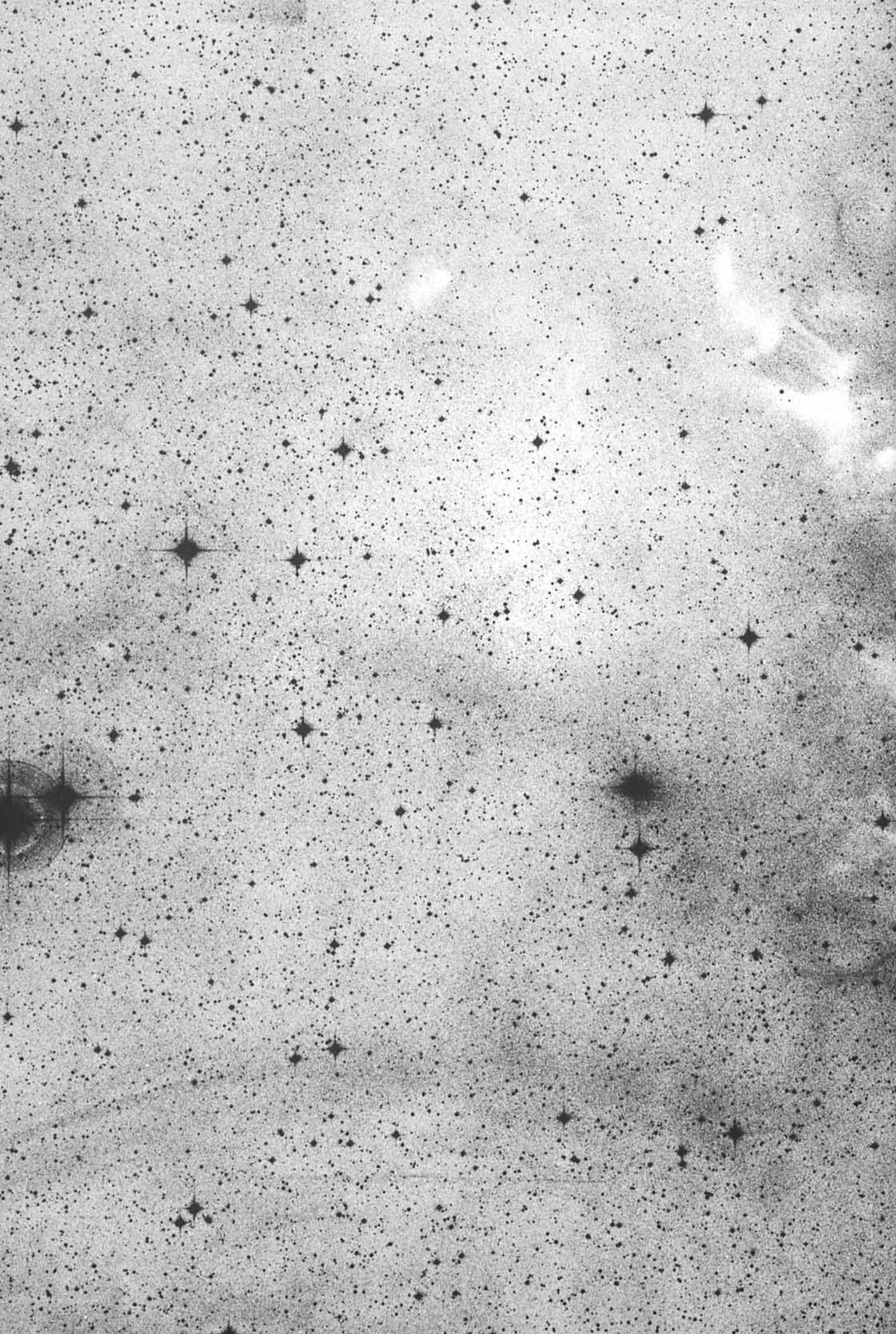
It should be noted that the selection of a [S II] 6717/6731 filter, rather than an Hα filter, is essential to this technique, as most stars show Hα emission, which will then also be present in the surrounding reflection nebula. [S II] emission is, on the other hand, a clear indicator of shocks, when associated with a low-mass, low-luminosity star. Van den Bergh (1975) employed an early version of this scheme.

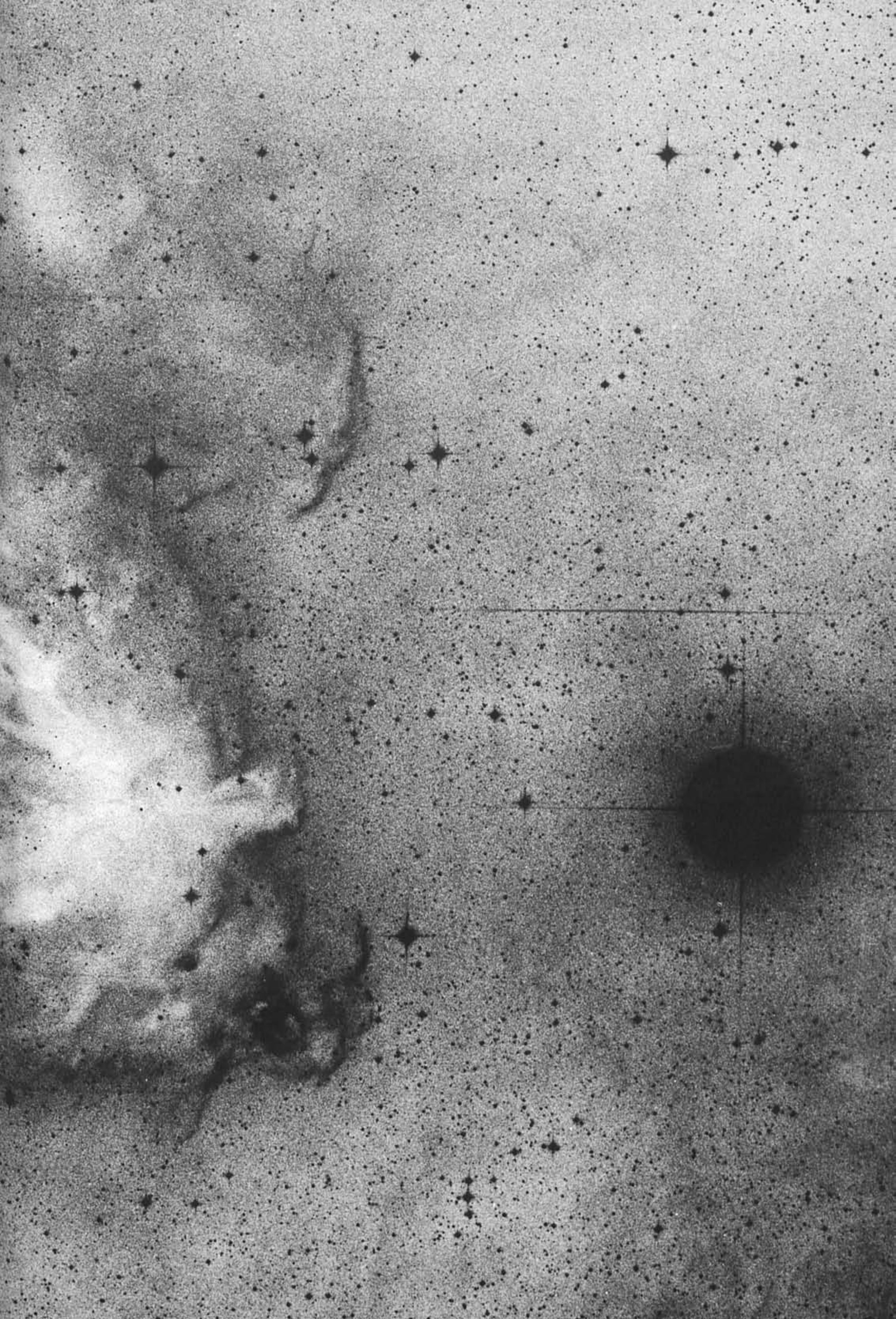
Such a survey has a value in providing firmer statistics on the frequency and timescales of shocked outflows from young stars. But it is the detailed follow-up observations of selected objects which provide the most fun and which occasionally can provide new insights on early stellar evolution. For example, the new objects HH 80/81 are almost as bright as HH 1 and 2 (the first objects to be discovered by Herbig and Haro and still the brightest), but they are at least three times more distant and are thus the intrinsically brightest objects known (Reipurth and Graham 1988). Moreover, they do not emerge from a solar-type star, but from a young B-star, and they show the highest velocity dispersion hitherto observed. Or take the case of the new object HH 111, probably the largest and best collimated jet known to date to emerge from a young star. Besides the jet it has four bow shocks, moving supersonically in pairs of two in opposite directions from an embedded infrared source, from which there also streams a large molecular flow (Reipurth, in press).

The Orion Region

The molecular clouds in Orion are the most active sites of low mass star formation known. Figure 3 shows a deep red Schmidt plate of the Orion nebula and beneath it the L 1641 molecular cloud stretching to the southeast. The whole region is full of many hundreds of Hα emission stars, variable stars, flare stars and infrared sources. The L 1641

Figure 3: *The cometary shaped molecular cloud L 1622 in Orion as seen on a deep red ESO Schmidt plate. The cloud is active in low-mass star formation, and contains many nebulous stars, Hα emission stars, infrared sources and one Herbig-Haro object.* ▶





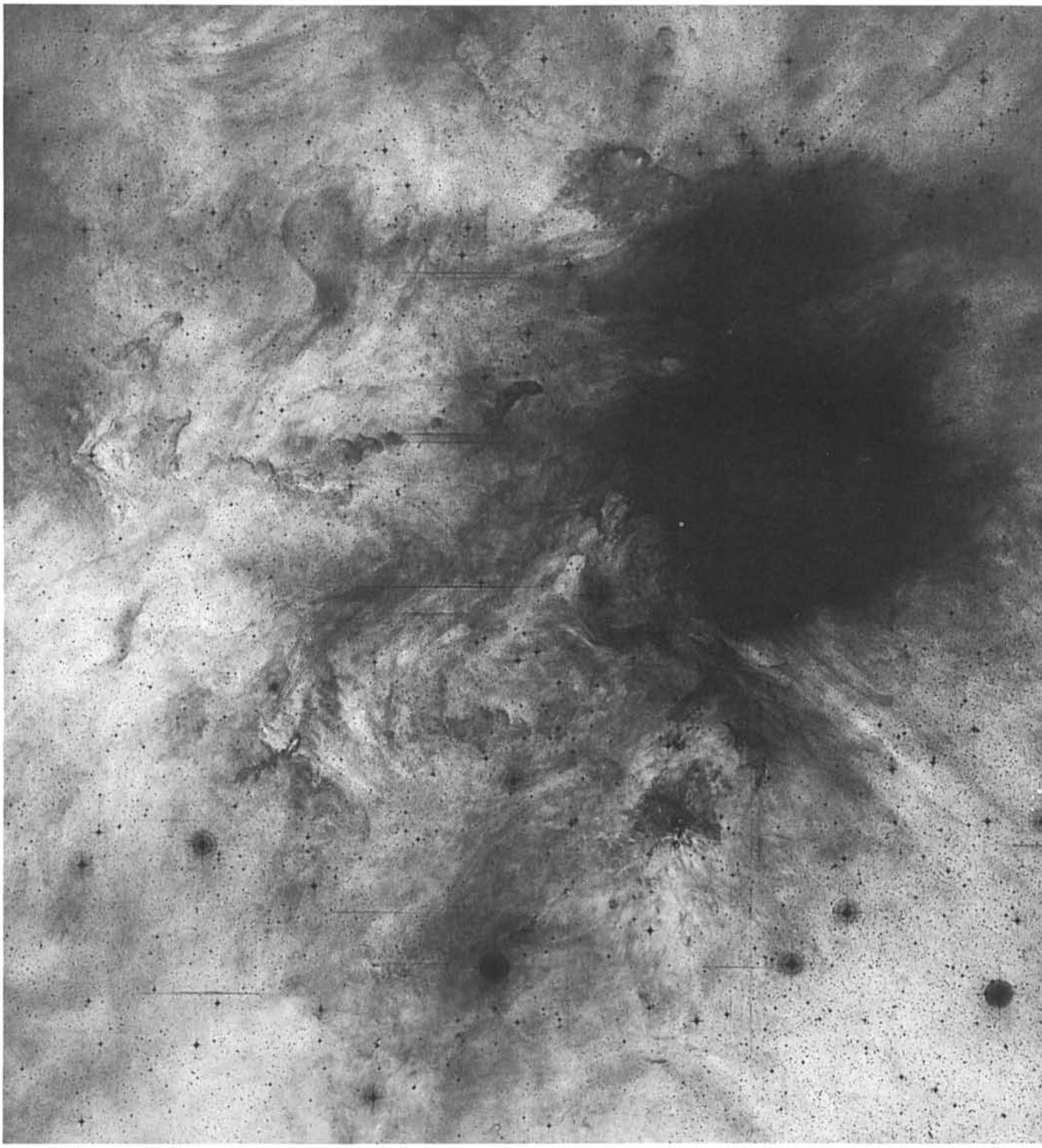


Figure 4: *A deep, red ESO Schmidt plate (IIIa-F, 150 min., RG 630) showing the Orion Nebula. The print was produced by subjecting the plate to unsharp masking, followed by diffuse-light amplification. As M42 itself is not interesting in this context, the mask was prepared in such a way that it would not influence M42 in any appreciable manner, but so that the low-surface-brightness filamentary structures stand out in great detail.*

cloud appears as a rather homogeneous obscuration, but a detailed map made at ^{13}CO by Bally et al. (1987) shows that the cloud is really composed of long infiltrated strings and clumps of denser material embedded in a lower density gas and dust environment. Closer examination of the region shows that the youngest stars, those found as infrared sources, are almost invariably located in association with the denser clumps.

The region is also rich in Herbig-Haro objects, indeed it has the highest concentration of such objects found anywhere. Star formation therefore has not only taken place here over the last few million years, but is a still ongoing process. Moreover, it is not confined merely to the dense L 1641 cloud. Figure 3 has been processed in such a way as to bring out the faint outlying structures, to which only little attention has been paid to date. Our survey uncovered several Herbig-Haro objects in these more peripherical regions, and shows that star formation also occurs here, albeit on a very modest scale.

Orion contains many smaller, less well-known clouds, in which stars are being born. Figure 4 (centerfold) shows the beautiful L 1622 cloud. With its bright rims and long tail it gives the impression of being strongly affected from the outside. It is in fact pointing directly towards the young massive O-stars in M42, which bath it in ultraviolet radiation. This outside influence may be the cause of the vigorous formation of stars occurring in this small cloud: there are several nebulous stars, Hα emission stars, and embedded infrared sources, and we have found a new Herbig-Haro object (HH 122, seen as a tiny group of small nebulae near the eastern edge of the cloud). A detailed optical infrared/radio study is currently being made of L 1622 at La Silla.

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Professors J.H. Oort, H. van der Laan and A. Blaauw looking at the La Silla model.

On Friday, January 27, Professor Adriaan Blaauw opened the ESO Exhibition in The Hague, the Netherlands, with a review of ESO's history since 1952. This was preceded by a speech from the Director General about ESO's future and its role in European astronomy.

Among many prominent guests were Prof. Jan Hendrik Oort and Dr. Henk Bannier, both former Presidents of the ESO Council, and the present members of Council, Prof. Wim Brouw and Dr. Jan Bezemer.

The Exhibit, which lasts till March 12, 1989, is hosted by the beautiful new Science Museum of The Hague called MUSEON. ESO is especially grateful to Dr. Wim van der Weiden, MUSEON's Director, for his enthusiastic reception. The Exhibit was set up by Mr. Claus Madsen of ESO and Dr. Peter Wisse, staff astronomer of MUSEON.

The festive opening was co-hosted by OMNIVERSUM, Europe's first space-theatre, next door to MUSEON. OMNIVERSUM openend in December 1984 and is the result of a sustained initiative by Prof. Harry van der Laan between 1977 and 1984, while he was Chairman of nearby Leiden Observatory.

Observation of the ^{12}CO (J = 1 → 0) Line in NGC 613 with the SEST

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Introduction

The availability of the Swedish-ESO Submillimeter Telescope (SEST) on La Silla opened the possibility of extending the radio observation of molecular lines to the very southern galaxies. In particular the observation of the CO lines in the nearest galaxies will permit not only to increase the sampling for statistical purposes but also to study in more detail the distribution and kinematical properties of the molecular clouds in relation to other components of the galaxies. The HPBW of the SEST, at the frequency of 115 GHz of the ^{12}CO (J = 1 → 0) line, is 43″ which means that galaxies with diameters between 5.5 and 10 minutes of arc are well suited for mapping since they do not require a prohibitive amount of time and the arms can be resolved if the inclination angle is adequate.

We had selected NGC 613 some time ago as a candidate for CO observation because of several interesting features,

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