THE STAR FORMATION NEWSLETTER

An electronic publication dedicated to early stellar evolution and molecular clouds

No. 7 — 6 Mar 1993 Editor: Bo Reipurth (reipurth@eso.org)

Abstracts of recently accepted papers

Clumpy Disk Accretion and Chondrule Formation

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Chondrules are the major constituent of most of the primitive meteorites, yet the mechanism of their formation is largely unknown. Chondrule textures and compositions place tight constraints on the thermal processing necessary to turn precursor dust aggregates into chondrules – temperatures between about 1500 K and 2000 K and cooling times of hours are indicated. As suggested by Hood and Horanyi (1991), shock heating within the nebula may be capable of matching the thermal constraints, provided that a suitable source of nebular shocks can be found. We suggest here that the source of the shocks possibly responsible for chondrule formation was episodic accretion onto the solar nebula of low-mass clumps ($\sim 10^{22}$ g) of interstellar gas. Three types of astronomical observations are best explained by the existence of opaque clumps that block stellar radiation while moving at high velocities within a few AU of young stellar objects: (a) rapid variations in stellar luminosity, independent of wavelength, (b) rapid changes in surface brightness of nearby reflection nebulae, and (c) rapid variations in spectral lines excited in circumstellar regions. While the origin of these clumps is presently unknown, they might arise from the inhomogeneous infall of the residual molecular cloud core, from the return of matter ejected by the stellar wind, or from a combination of these two effects. Infalling clumps will impact the protoplanetary disk at high velocity, producing a localized, intense source of heat suitable for chondrule formation. As the resulting shock wave propagates into the nebula, pre-existing aggregates of dust grains formed in the nebula will be melted by the shock front, producing chondrules. For reasonable estimates of the clump impact rate onto a minimum mass nebula, we find that a non-negligible fraction of the nebula mass undergoes the required thermal processing. Clumpy disk accretion is a mechanism that is capable of providing a long-lived, late-phase, episodic, and variable intensity source of cyclical thermal processing for chondrule precursor grains.

Accepted by Icarus

COYOTES I. Multisite UBVRI Photometry of 24 Pre-Main-Sequence Stars of the Taurus-Auriga Cloud

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We present the results of a multi-site photometric campaign to monitor T Tauri stars in the Taurus-Auriga stellar formation region. The campaign — dubbed COYOTES, for **C**oordinated **O**bservations of **Y**oung **S**tellar **O**bjec**T**s from **E**arthboud **S**ites — yielded UBVRI magnitudes of 13 classical T Tauri stars, 10 weak-line T Tauri stars, and one suspected Ae Herbig star during 3 months between November 1990 and February 1991. This database is well suited to search for periodic variations from about 1 day up to around 6 weeks, significantly extending the range of timescales properly sampled for T Tauri stars. We find evidence for periodic light variability in all 24 stars of our sample. More precisely, photometric periods are detected in 18 stars at or above the 90% probability level in several photometric bands simultaneously (BD+24^{o}676, DF Tau, DG Tau, DI Tau, DK Tau, DR Tau, GG Tau, GK Tau, IP Tau, RY Tau, GM Aur, LkCa-15, IW Tau, LkCa-4, LkCa-7, LkCa-19, TAP 26, TAP 40), while probable periods, which require confirmation, are reported for 4 other stars (DE Tau, LkCa-21, TAP 41, TAP 57NW), and upper limits on the photometric period are derived for the 2 remaining stars (SU Aur, TAP 9). Light curve analysis and the origin of the variations are discussed in a companion paper (Bouvier et al. 1993, Paper 2).

Accepted by A&A, Supp. Ser.

COYOTES I. The Photometric Variability and Rotational Evolution of T Tauri Stars

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In a multi-site photometric campaign to monitor T Tauri stars (TTS) in the Taurus-Auriga cloud over more than two months – dubbed Coordinated Observations of Young ObjecTs from Earthbound Sites (COYOTES) –, we find all 24 of our target stars show evidence for *periodic* light variations with periods between 1.2 and 24.0 days. This more than doubles the number of periods published for Tau-Aur TTS. The variations of 20 of these stars can be interpreted as rotational modulation of the stellar flux by surface spots. The periods of the four remaining stars (RY Tau, BD+24^{o}676, TAP 26, and LkCa-21) may correspond to orbital periods of binary systems. Models of the UBVRI light curves lead to the properties of the spots, both hotter and cooler than the photospheric temperature, which appear to be the principal source of the photometric variability of TTS on timescales of days and weeks.

The longest rotational period we measure (12 d, for GM Aur) leads to an equatorial velocity of 8 km/sec, which confirms the paucity of extremely slow rotators ($V_{eq} << 10$ km s^{-1}) among TTS younger than 5 10^6 yrs. Combining our 20 rotational periods with those published for 17 other Tau-Aur TTS, we find that the Weak-line TTS (EW(H_α) <10Å) rotate faster than Classical TTS (EW(H_α)≥10Å) at the 99.9% confidence level (according to a K-S test). The mean rotational period for the 11 WTTS is 4.1 ± 1.7 d; for the 15 CTTS, 7.6 ± 2.1 d. We interpret this difference as evidence that WTTS spin-up as they contract on their convective tracks, while CTTS are prevented from doing so by either (a) their strong winds carrying away excess angular momentum and/or (b) a magnetic coupling between the stars and their inner accretion disks, as suggested by recent models. We discuss the implications of this interpretation for the subsequent evolution of TTS toward the main sequence. In particular, we propose that the different rotational histories of WTTS and CTTS on their convective tracks may account for the large range of rotational velocities observed among low-mass dwarfs in young clusters.

Accepted by A&A, Main Journal

A spectral atlas of the Herbig Ae star AB Aur: the visible domain from 391 to 874 nm

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The visible spectrum of the pre-main-sequence Herbig Ae star AB Aur (A0Ve), recorded by the MUSICOS echelle spectrograph, was used to elaborate a high resolution (R = 38000) spectral atlas, with line identification, in the wavelength range 391-874 nm. The numerous spectral features were individually measured and their identification was carried out with the help of a synthetic spectrum and a laboratory wavelength list for relevant atomic species.

For 120 spectral features present in the spectrum, we identified contributions from about 215 lines. The presence of 19 ions from 15 different elements is firmly established.

From the analysis of several well-defined photospheric lines, we determined for AB Aur a $vsini$ value of 80±5 kms^{-1}.

From a detailed comparison of the photospheric lines with the synthetic spectra calculated with classical photospheric models of Kurucz (1979), we deduced an effective temperature $T_{eff} = 10220^{+150}_{-100}$ K and a surface gravity $log(g) = 4.10 \pm 0.06$.

Upper limits were derived for the veiling of photospheric lines reaching from 3.5% at 4500A to 16% at 6100A. If AB Aur possesses an accretion disk with an optically thin inner region, as conjectured by Hillenbrand et al. (1992), then the absence of veiling implies an accretion rate lower than 7.5×10^{-8} $M_{\odot}yr^{-1}$.

The spectral lines in the spectrum of AB Aur can be classified in 6 categories: photospheric lines identical to those of a synthetic spectrum calculated with a classical photospheric model; lines with filled-in cores; asymmetric absorption lines; emission lines; lines which are deeper than predicted; P Cygni profiles for the first lines of the H I Balmer series. All these different features are consistent with a model including a photosphere with $T_{eff} = 10000$ K and $log(g) = 4$, an extended chromosphere with a temperature reaching 17000 K, and a stellar wind.

The regions of formation of a set of typical lines of this spectrum were compared with each other, by computing absorption coefficients at line center, using an existing atmospheric model for AB Aur.

Accepted by Astron. Astrophys.

The Association of ^{13}CO Molecular Gas with IRAS Sources in L1641

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^{13}CO observations with 2'.7 angular resolution were made of IRAS sources in L1641 to test the association of ^{13}C dense cores with young stellar objects. The sample include 40 IRAS sources, 8 of which are associated with CO molecular outflows, and the other 32 nonoutflow sources. We find that 6 of 8 outflow sources are associated with molecular dense cores, compared to only 5 of 32 outflow sources. We also find that the cold IRAS sources, including 7 of the 8 outfloe sources tend to be more luminous and associated with higher ^{13}CO column density than the rest. Our results suggest that the dense cores are dissipated by the high-velocity molecular outflow in the early stage of star formation. This is consistent with the star formation scenario proposed by Shu, Adams, and Lizano.

Accepted by Astrophysical Journal

Discovery of a Cold and Gravitationally Unstable Cloud Fragment

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1300 μm mapping of the region around the energy source of HH 24 in the dark cloud L1652 has revealed a neighbouring strong, previously unknown source of dust emission. Photometry at 450, 800, 1100 and 1300 μm yields a very low dust temperature of around 10 K. Estimates for the mass of the object lead to values of 36 and 52 $M_{\odot}$ for radii of $4.1 \cdot 10^{16}$ and $8.2 \cdot 10^{16}$ cm, which is at least a factor of 50 above the Jeans mass. The 1300 μm contours show an elongation along N-S and a strong central increase in density. These observational facts lead us to suggest that we have detected a cold and gravitationally unstable cloud fragment which might be a protostar.

Accepted by Astron.Astrophys. (Letters)

The Orion Radio Zoo Revisited: Source Variability

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The core of the Orion nebula has been monitored with the VLA in the A and B configurations at 5 and 15 GHz over a period of 7 months. A region of 0.2 pc centered on the Trapezium cluster was imaged about every two weeks at both frequencies. The goal was to study possible temporal variations of flux density and spectral index of a large number of very compact radio sources near the Trapezium cluster.

The binary system θ^1Ori A is the most variable source in the sample. Although some modulation of emission with orbital phase might be present, the main source of variability appears to be intrinsic and not related to orbital phase; possibly flaring activity on the surface of the T Tauri companion.

All of the other radio sources are classified as thermal or nonthermal depending on their variability, spectral index, angular size, and optical identification. The thermal sources are clustered close to θ^1Ori C (with the exception of BN and IRc2). We suggest that the thermal sources near θ^1Ori C that are coincident with visible stars may be photoionized envelopes (due to UV radiation from θ^1Ori C) of accretion disks around low mass stars. In the spirit of Garay (1987), we refer to these objects as EIDERS=Externally Ionized (accretion) Disks in the Environs of Radiation Sources which O'Dell *et al.* (1993) call PROPLYDS. The thermal radio sources that are not coincident with visible stars are probably neutral condensations whose outer envelopes are ionized by UV radiation from θ^1Ori C. The latter are sometimes referred to as PIGs (partially ionized globules). The nonthermal sources are scattered over a larger area. Premain sequence flaring activity is proposed as the source of radio emission. For the brightest nonthermal sources a correlation between spectral index and flux density is found, which can be explained qualitatively by synchrotron emission in a magnetic loop.

Accepted by Astron. Astrophys. Suppl.

High-resolution spectrophotometric imaging of the Herbig-Haro object HH 29 in the L 1551 outflow

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We have obtained narrow-band images of the Herbig-Haro object HH 29 in a number of important shock diagnostic emission lines under excellent seeing conditions. Some 25% of the total line flux originates from a resolved compact source which makes up only 4% of the projected emitting area of HH 29. This feature shows a marked elongation in the same direction as the molecular outflow emanating from the young stellar object L 1551-IRS 5. The essentially extinction-free [O III]/Hβ ratio delineates the spatial distribution of the gas heated by strong shocks. For these regions the extinction map, derived from Hα and Hβ observations, shows a patchy dust distribution on scales of a few hundred AU and with column density contrasts of about 2–6. The distribution of the [O I], [O II] and [O III] emission indicates pre-shock densities $\geq$ 300 cm^{-3} and bow shock velocities of about 90 km s^{-1}. The cooling zone appears spatially resolved in the principal direction of the shock flow.

Accepted by Astron. Astrophys.

Star formation in L1251: Distance and members

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We have obtained a distance of 300 ± 50 pc for the dark cloud L1251 by measuring the colour excess values of 52 field stars around the cloud. In order to find the stars born in L1251, we have combined the information extracted from the IRAS observations with the results of a Schmidt survey for Hα emission stars. Twelve optically visible emission line stars are found within the cloud area. These objects are most probably T Tauri stars. In the same area there are 16 IRAS point sources with fluxes typical of young stellar objects. They form a heterogeneous group containing objects in various evolutionary stages. Five of the Hα emission stars were also detected by IRAS and their pre-main-sequence nature can be considered relatively certain. The infrared sources without an optical counterpart are probably the youngest members of the stellar population in the cloud. The most deeply embedded objects are projected on an ammonia core in the western part of L1251. Despite their position in the presumed birth place of stars, these objects have too low luminosities to be in the main accretion phase of protostars.

Accepted by Astron. Astrophys.

Formaldehyde as a Probe of Physical Conditions in Dense Molecular Clouds

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We present a detailed analysis describing the utility of the formaldehyde (H_2CO) molecule in the derivation of the kinetic temperature and spatial density within molecular clouds. Measurements of thirteen transitions from both the ortho and para species of H_2CO have been made toward a sample of eleven active star formation regions. These H_2CO transitions range in frequency from 211 to 365 GHz and in upper state energy from 21 to 241 K. This range in excitation has allowed us to analyze H_2CO sensitivity to both cool ($T_K \leq 50$ K) and warm ($T_K > 50$ K) molecular material.

Using a spherical large velocity gradient model to solve for the excitation of H_2CO, we analyze the sensitivity of several ortho- and para-H_2CO transition intensity ratios to the kinetic temperature and spatial density within molecular clouds. Through this analysis we derive several "rules of thumb" which should be followed when measurements of a particular intensity ratio are used to calculate T_K or n(H_2) in a molecular cloud. We find that for $T_K \leq 150$ K and over ranges in H_2CO column density typical for most molecular clouds several H_2CO transition intensity ratios are excellent monitors of T_K and n(H_2). Since the transitions whose relative intensities are sensitive to kinetic temperature can be measured using the same receiving system (and can in some cases be measured within the same spectrum), calibration uncertainties are minimized. We also present a detailed analysis of the uncertainties encountered in our modelling procedure, including the potential importance of infrared excitation.

Using our measured H_2CO radiation temperatures we have constrained LVG model solutions for the kinetic temperature, spatial density, and H_2CO species column density in each of the sources in our sample. Our derived spatial densities are comparable to those estimated using other molecular tracers. In all of the regions in our sample, though, we measure kinetic temperatures > 50 K, significantly higher than previous estimates for many of these sources. Previous underestimation of T_K is due to the use of tracers which are sensitive only to cool ($T_K \leq 50$ K) gas. In particular, temperatures of 100 K or more occur toward both the cool young binary object IRAS 16293−2422 and toward the "protostellar condensations" FIR4/FIR5 in NGC 2024. Using our ortho- and para-H_2CO measurements we have calculated the $\frac{N(ortho-H_2CO)}{N(para-H_2CO)}$ ratio in several of the sources in our sample. Our measurements indicate that $\frac{N(ortho-H_2CO)}{N(para-H_2CO)} < 3$ for most of our sources. When combined with the relatively high kinetic temperature in these objects, this $\frac{N(ortho-H_2CO)}{N(para-H_2CO)}$ ratio suggests that dust grains might play an active role in H_2CO chemistry.

Accepted by Astrophys. J. Suppl.

The Exciting Sources of Herbig-Haro Objects. I. A Catalogue of 1-20μm observations.

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For 58 exciting sources of Herbig-Haro objects/jets (HHES) we present a catalogue of photometric data for the infrared spectral bands JHKLMNQ (1-20μm). This catalogue is based on our own observations and published information available up to May 1992. For each source, these data are presented in chronological order. In addition to the broad-band data, narrow-band N(8-13 μm) photometric data are also provided. The flux calibration for each observational equipment is explicitly noted as are the diaphragm sizes used. The same kind of information for the established members of the FU Ori class is complementing the HHES catalogue. The frequency of observations and the photometric quality of the catalogued data are shortly discussed.

Accepted by Astron. & Astrophys. Suppl. Ser.

Discovery of New Objects in the Orion Nebula on HST Images: Shocks, Compact Sources, and Protoplanetary Disks

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We have reduced and analyzed a set of narrow-band HST images of a portion of M42 south of the Trapezium. Many new emission line sources were found, some quite long but so narrow that they are not seen on groundbased images. These include thin shells which are high ionization shocks. The structure around Orion HH3 is resolved into multiple components. Slit spectroscopy data establishes the high expansion velocities of these regions. The other objects seen are compact sources. Although some had been detected in VLA surveys and several had been seen from the ground optically, the new images show previously undetected structure and clearly establishes that most are protoplanetary disks, which are neutral disks surrounding low mass pre-main sequence stars and are ionized from the outside by θ^1C and θ^2A Ori.

Accepted by Astrophys. J.

Classification and statistical properties of galactic H_2O masers

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The association between galactic H_2O masers and IRAS sources from the Point Source Catalog is established for 442 sources out of a list of 505 objects, which includes all the galactic H_2O masers north of $-30°$, known up to 1988.

Using a multivariate statistical analysis on the four FIR fluxes of the associated IRAS source, galactic H_2O masers are reclassified into two classes: those associated to star forming regions (SFR, 52%) and those associated to late type stars (STAR, 45%). The remaining 3% cannot be included in either class. The present classification is compared with others in the literature.

Distances for a large sub-sample of H_2O masers are derived, using the galactic rotation curve for SFR and literature data for STAR.

The parameters of the H_2O maser emission (e.g. integrated flux, luminosity, variability), collected in a homogeneous way in the Arcetri H_2O atlas (Comoretto et al. 1990), and those of the associated IRAS sources (e.g. flux density, luminosity, colours) are used to investigate, in a statistical way, the properties of the STAR and SFR classes.

In particular, we investigate the spatial distribution of masers both in the galactic plane and perpendicular to it. We also compare the H_2O and IRAS luminosities, finding a good correlation. Moreover, we find that high luminosity sources show low colour temperatures and viceversa. The spectral profile and variability are then investigated by different means. Finally, the luminosity function for each maser class is derived.

Accepted by Astron. Astrophys.

Molecular Outflows Entrained by Jet Bowshocks

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Recent high-resolution observations of CO outflows often reveal well-collimated emitting regions with radial velocities that increase away from the outflow source ("accelerating" outflows), surrounded by limb-brightened low-velocity emission. There is growing evidence that molecular flows exhibiting this structure are driven by high-velocity, possibly time-variable, narrow jets. In order to better understand the dynamical interaction between such jets and the large-scale outflow, we present a simple, analytic model in which the molecular outflow corresponds to environmental gas entrained in the wake of a bowshock created by an internal jet working surface. This model results in flows with velocity and density structures that appear to be similar to the observed "accelerating" molecular flows. The model also gives global outflow shapes that are comparable to the observed ones, and predicts a higher collimation for less energetic flows (*i. e.*, for lower luminosity sources), in agreement with reported trends.

Accepted by Astron. Astrophys.

A Unified Stellar Jet/Molecular Outflow Model

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We present a coupled stellar jet/molecular outflow model. In this model, the stellar jet is assumed to have a large number of "internal working surfaces" that intercept material from the jet beam and eject it sideways into the near environment. This sideways ejection of mass and momentum leads to the formation of a "turbulent envelope" in which the jet material is mixed with entrained environmental gas. Under the assumption that the jet has a large number of internal working surfaces (which would probably be the case for an evolved outflow), we derive a simple theoretical framework for describing this flow. We then use this model to obtain predictions of intensity maps and position-velocity diagrams which can be directly compared with observations of molecular outflows. We also discuss the general characteristics predicted from our model, which apparently show a good qualitative agreement with observations of molecular outflows. However, our model appears to predict a somewhat too high degree of collimation for the molecular outflows. This discrepancy could be a result of the simple parametrization which we have adopted for the description of the turbulent flow.

Accepted by Astron. Astrophys.

Pure Fluorescent H_2 Emission from Hubble 12

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An improved K-band (2.0 μm - 2.4 μm) spectrum of the planetary nebula Hubble 12 has been obtained at a position near where Dinerstein et al. (1988) found the H_2 line emission to be fluorescent. The new spectrum is consistent with the conclusion of Dinerstein et al. and, in addition, provides further evidence that the emission is essentially purely fluorescent through the presence of several weak H_2 lines of higher excitation than had been detected previously and

a measured ortho/para ratio of 1.7. Analysis of the spectrum demonstrates that the gas density is $\sim 10^4 - 10^5$ cm^{-3}.

Accepted by Mon. Not. R. astr. Soc.

A High Sensitivity Survey of Radio Continuum Emission from Herbig Ae/Be Stars

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We present results of a high-sensitivity VLA/Australia Telescope survey of radio continuum emission from the 57 Herbig Ae/Be stars and candidates in the 1984 catalog of Finkenzeller and Mundt. A total of 12 stars (= 21%) were detected, and an additional 4 stars are classified as possible detections. Several lines of evidence suggest that the radio continuum emission from Herbig Ae/Be stars is predominantly thermal and in many cases wind-related. Nonthermal emission seems likely only for the eclipsing binary TY CrA, and also remains a possibility for MWC 137. However, the classification of these two objects as Herbig Ae/Be stars is in doubt.

There is a paucity of radio detections later than spectral type ≈A2, and the inability to detect later A-type stars is attributed to the rapid decrease in wind ionization toward lower effective temperatures. Although the number of radio detections is small, the available data suggest a correlation between 3.6 cm luminosity and bolometric luminosity with a near-linear power law dependence of the form $L_{3.6cm} \propto L_{bol}^{+0.9\pm0.1}$. A comparison of the observed radio fluxes with those predicted by simple, spherical free-fall accretion models indicates that accretion rates for Herbig Ae/Be stars have previously been overestimated, or that the accretion process is sufficiently complex that spherical free-fall theory does not apply.

Accepted by Astrophys. J. Supp.

Tidally-induced Warps in T Tauri Disks. I. First-Order Perturbation Theory

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We study the perturbation caused by a stellar companion on the potential of a T Tauri disk in the first-order approximation. We compute the resulting disk warp as a function of stellar and disk parameters in both cases of self-gravitating and accretion disks. We then calculate the radiative flux emitted by the warped disk, considering heating by both viscous accretion and reprocessing of stellar light. We predict that T Tauri stars with tidally warped circumstellar disks may display far-infrared and submillimetric radiative flux well in excess of that expected from flat circumstellar disks.

Accepted by Astron. Astrophys.

The Formation of Protostellar Disks. I. 1 $M_\odot$

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Hydrodynamical calculations of the collapse of an axisymmetric, rotating 1 $M_\odot$ protostellar cloud, including the effects of radiative transfer and radiative acceleration but without magnetic fields, are presented. The results include calculations of infrared protostellar spectra as a function of time and viewing angle. A numerical algorithm involving explicit nested grids (ENG), applied to this particular problem for the first time, is used to resolve the region of initial disk formation (5-500 AU) and at the same time to include the outer regions ($\sim$ 3000 AU) in the calculation. The central part of the protostar, interior to 5 AU, is not resolved numerically but is modelled approximately. Initial conditions are systematically varied to investigate their influence on the evolution and final configuration of central star plus circumstellar disk. The initial state for the standard case is a centrally condensed molecular cloud core of 1 $M_\odot$ with a mean density of 8×10^{-18} g cm^{-3} and a specific angular momentum at the outer edge of 7×10^{20} cm^2 s^{-1}. The collapse is followed for 8×10^4 yr, at which point 0.45 $M_\odot$ is contained in a rapidly rotating central object and

most of the remainder in a surrounding equilibrium disk. The stability of this final structure is qualitatively analyzed; it is likely to evolve further as a consequence of gravitational torques.

Accepted by Astrophys. Journal

Near-infrared Discovery of the L810 Nebula Illuminator

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As part of a deep near-infrared imaging survey for infrared point sources in Bok globules, we have discovered the illuminator of the optical reflection nebula seen towards the Bok globule L810. The illuminator (L810IRS) is located at the position predicted by Scarrot et al. from analysis of their optical polarimetry. This source is very red ($J-K \sim 3.9$), bright ($m_K = 10.7$) and has an estimated bolometric luminosity of $890 L_\odot$. Additionally, we found a near-infrared nebula which extends 20 arcsec symmetrically to the north and to the south of L810IRS, exhibiting an hourglass shape. Both the morphology and the orientation of the near-infrared nebula are in good agreement with the morphology and orientation of the high-velocity molecular outflow associated with L810. Finally, we found a near-infrared jet-like structure whose axis is colinear with L810IRS. Together, these findings indicate that L810IRS is likely to be a deeply embedded, very active intermediate-mass young stellar object within the L810 cloud.

Accepted by Astrophysical Journal Letters

Meetings

Gordon Conference on Origins of Solar Systems

July 5 to July 9, 1993

Colby-Sawyer College, New London, New Hampshire

Chair: Dr. John Wood, Center for Astrophysics 60 Garden Street, Cambridge, MA 02138

Attendance will be limited to 135 scientists.

Applications are available from: (due 6 weeks prior to conference) Dr. Alexander M. Cruickshank, Gordon Research Conferences, Gordon Research Center, University of Rhode Island, Kingston, Rhode Island 02881-0801. Telph. (401)783-4011

The Nature and Evolutionary Status of Herbig Ae/Be Stars

October 26-29, 1993

Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

The aim of the conference is to review the major scientific accomplishments in the study of Herbig Ae/Be stars up to 1993, and to outline the major problem areas for future research in this field. Every aspect of the nature of these objects will be discussed. In particular, new insights on the evolutionary status of these objects and the properties of their circumstellar disks will be addressed.

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