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EXPECTATIONS FROM NEW INSTRUMENTS

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RESUMEN

Con la nueva generación de instrumentos habrá grandes oportunidades de avanzar en el estudio de la formación estelar. En particular, las grandes mejoras en las sensibilidades y resoluciones angulares de las observaciones nos permitirán ver y resolver discos alrededor de estrellas jóvenes, estudiar y caracterizar las partes internas de los discos donde se supone que se generan los vientos magnetocentrífugos y, quizás, detectar objetos planetarios en otros sistemas solares. Además, algunos de esos nuevos instrumentos funcionarán en bandas de longitud de onda hasta ahora difícilmente accesibles. Esas nuevas *ventanas* seguramente nos proporcionarán inestimables pistas sobre las condiciones detalladas en que se forma una estrella, cómo se forman los discos y cómo se generan los vientos y flujos.

ABSTRACT

With the new generation of instruments about to come on line, there will be great opportunities to make advances in the study of star formation. In particular, great improvements in terms of sensitivity and angular resolution will allow us to look for and resolve disks around young stars, to study and characterize the inner disk areas where magnetocentrifugally driven winds are supposed to be launched, and perhaps to detect planetary objects in other solar systems. Furthermore, some of these new instruments will operate in new wavelength bands, which heretofore have not been easily accessible. These new *windows* will surely provide us with invaluable clues on the detailed workings of how to make a star, how to make the attending disks, and how to drive the winds and outflows.

Key words: **ISM: DUST, EXTINCTION — ISM: MOLECULES — STARS: CIRCUMSTELLAR MATTER — STARS: PLANETARY SYSTEMS**

1. INTRODUCTION

If one is not blessed with strong beliefs or dogmas, there will be a wish to explore with increasingly better instruments in order to seek "truth" and "knowledge". In astronomy, the last quarter of the twentieth century has seen a tremendous revolution in sensitivity and resolution that is perhaps unparalleled in other disciplines. By building larger and larger telescopes with more and more sensitive detectors, astronomers can now essentially look out to the very edge of our universe. In this paper, we will briefly forecast how the next generation of telescopes will help us solve some of the most pressing problems in star formation. This conference has reviewed in detail a wide range of phenomena which has focussed all of our attentions over the past decade. It is not possible to discuss them all in the context of what to do next. We will select just a few problems here.

2. NEW TELESCOPES

The game plan is very straightforward. The goal is to explore as much of the parameter space available to us as is practical. By practical, we mean of course in terms of technology and cost. The principal parameter spaces which can be attacked are wavelength, resolution, and sensitivity. Past experience tells us that a good rule of thumb is to make improvements at least by an order of magnitude. Whereas factors of 2 are very significant, funding agencies almost always are preoccupied with larger numbers.

We review here the status of some of the new telescope projects which are either being built or being planned. It is very impressive that so many projects are in fact underway. As has been seen throughout this conference, the high angular resolutions provided by instruments such as the Very Large Array (VLA) and the Hubble Space Telescope (HST), have been the key to resolving disklike structures around very young stars and also the optical and radio jets emanating from them.

2.1. Subaru

The 8.3 m Subaru telescope is under construction by the Japanese National Astronomical Observatory on Mauna Kea in Hawaii. Its foundation and control building have already been built, and its mirror has been cast by Corning and is currently being polished by the Contraves large optics facility. This telescope will have infrared capabilities and adaptive optics capabilities. The mirror itself should be ready for shipping to Hawaii in 1997 with first light being planned for 1999. The Subaru is part of the new revolution in optical instruments. A number of other large optical telescopes are being constructed, including the Gemini telescopes on Mauna Kea and Chile, and the Very Large Telescope (VLT) being built by the European Southern Observatory (ESO) in Chile. In addition to the increase in collecting area, the new generation of telescopes are being built with special attention to local seeing effects. Furthermore, the development of adaptive optics will ensure the achievement of sub-arc-second resolution from the ground.

2.2. Keck Interferometer

In addition to Keck I and Keck II, which have 10 m apertures, there are plans for 4 1.5 m outriggers to form a 6-element interferometer. This would be a next generation instrument over the optical interferometers which are operating at the moment, because of the tremendous collecting area being added by including the Keck telescopes. The resolution for optical interferometers on 100 m baselines is better than $10^{-3\prime\prime}$. Caltech's Keck interferometer or the ESO's VLTI may be able to detect planets by astrometric observations of the wobble of the stars due to the planet's orbit.

2.3. MMA

The U.S. National Radio Astronomy Observatory (NRAO) has proposed to build a large Millimeter Array (MMA) with a collecting area of about 2000 m^2. The concept is 40 8 m telescopes which can be reconfigured in four rings with diameters of 70 m to 3 km. The wavelength coverage will be from 7 mm to 1 mm, with emphasis on the shortest wavelengths. Leading candidate sites for this array are on Mauna Kea in Hawaii, and in northern Chile. This array will get down to $0.1''$ resolution, and will be a very powerful instrument for studying protoplanetary disks. If funding is approved by 1997, it can be completed by 2005. The MMA represents an order of magnitude improvement over existing millimeter arrays such as Berkeley Illinois Maryland Array (BIMA), Owens Valley Radio Observatory (OVRO), Nobeyama Millimeter Array (MMA), and Institut de Radio Astronomie Millimètrique (IRAM). Currently, the NRAO is working on the design of the telescopes, and the testing of the opacity and phase stability at their candidate sites. In collaboration with BIMA and OVRO, the NRAO is also working on technical development issues.

2.4. LMSA

The Japanese Nobeyama Radio Observatory has also proposed to build a Large Millimeter and Submillimeter wavelength Array (LMSA). The concept for the LMSA differs from the MMA by requiring almost 4000 m^2 of collecting area and operating down to 0.35 mm. There would be 50 10m telescopes, again reconfigurable to accomodate baselines as long as 2 km. With so many telescopes, the instantaneous (u,v) coverage will be excellent so that high dynamic range maps can be made in the snap-shot mode. This project is doing site testing in northern Chile and is considering the Mauna Kea site in Hawaii also. Both opacity and phase stability monitors have been fielded in Chilean sites. With a goal of $0.1''$ at 1 mm wavelength, and higher resolutions possible at even shorter wavelengths, this array will be particularly powerful in studying faint dust emission. The LMSA will have 20 times more collecting area than the Submillimeter Array (SMA) (see below) and will be a tremendously more powerful instrument. If all goes well, the initial funding of LMSA may be in 1998.

2.5. SOFIA

The proposed replacement for NASA's Kuiper Airborne Observatory (KAO) is the 2.5 m telescope of the Stratospheric Observatory for Infrared Astronomy (SOFIA). Because the Boeing 747 jet can fly at a sufficiently high altitude to get above the water in the atmosphere, far-infrared observations can be carried out. An angular resolution of 8″ wil be achieved at 100 μ. Although this is not as good as the resolutions which can be achieved with interferometers at mm and submm wavelengths, SOFIA operates at the peak of the blackbody curve for 20-50K material. Hence faint dust features and far-IR lines can be studied handily. The FY96 NASA budget includes funds for starting the development of SOFIA. If this is approved by congress, SOFIA will fly at the end of 2000. This will be a tremendous boost for studies in the far-IR.

2.6. SWAS, ISO

Two satellite projects, the NASA Submillimeter Wavelength Astronomical Satellite (SWAS), and the ESA Infrared Space Observatory (ISO), are about to be launched in 1995. The SWAS 54x68 cm telescope will have roughly a 4′ beam at 500 GHz. H_2O and O_2, whose lines are blocked by the earth's atmosphere, are the principle targets for the three year mission of SWAS. The molecular lines of these molecules are expected to be the dominant coolants of molecular clouds. The ISO 60 cm telescope will cover the near-IR to the far-IR with photometers, polarimeters and spectrometers. Array detectors are also available to cover 2.5–17 μ for imaging purposes. Direct imaging of dusty disks around protoplanetary systems is one of the principle targets of the 18 month mission of ISO.

2.7. SMA

The Smithsonian Astrophysical Observatory (SAO) is currently constructing the Submillimeter Array on Mauna Kea in Hawaii. The mission of the SMA is to achieve a collecting area equal to the largest existing single element submillimeter telescope, and to improve upon currently available angular resolution by at least one order of magnitude. The SMA consists of 6 6 m telescopes arranged in roughly a hexagonal pattern which can be reconfigured to a maximum diameter of about 500 m. The SMA will operate between 1.3 mm and 0.35 mm with angular resolutions as fine as 0.1″. In addition to a number of important lines in the submillimeter window, the highest angular resolution for studying dust emission will be achieved in this wavelength band. For the bulk of the material which is associated with star formation (20–100 K), the peak of the blackbody curve is in the far-IR, which is inaccessible from the ground. Only the airborne observatory KAO and its successor SOFIA can study this window. The closest one can approach the peak of this radiation in ground-based observations is in the submillimeter. Interferometry at submillimeter wavelengths has already been demonstrated by linking the Caltech Submillimeter Observatory (CSO) telescope and the Jamex Clerk Maxwell Telescope (JCMT). The SMA will be the first imaging interferometer in the submillimeter wavelengths. Although the SMA has a rather modest collecting area, calculatons show that it can image every molecular cloud core and every outflow source in the Galaxy. Figure 1 shows the calculated spectrum toward a typical dense cloud core with the SMA. Resolving the dust emission in star forming regions will be one of the primary targets of the SMA. The SAO is currently assembling its first two telescopes at a facility near Haystack Observatory in Massachusetts. A new correlator chip has been designed and manufactured, and the correlator itself will now be built. Prototype SIS receivers for the lowest three wavelength bands are being completed. The first telescopes are expected to be completed by the end of 1995. Pointing tests, holography tests for setting the panels, and interferometry tests will be performed before shipping the telescopes to Hawaii. The target date for having a completed array on Mauna Kea is currently the end of 1997.

3. NEW INSTRUMENTS

While new telescopes are being constructed, various other means can be employed with existing telescopes in order to improve sensitivity and wavelength coverage. Here we will mention just a few of these new developments.

3.1. Adaptive Optics

A number of groups have been successfully pushing the technique of adaptive optics. By stimulating the sodium line in the mesosphere (90 km high) with a laser, an artifical star is created for measuring the phase front

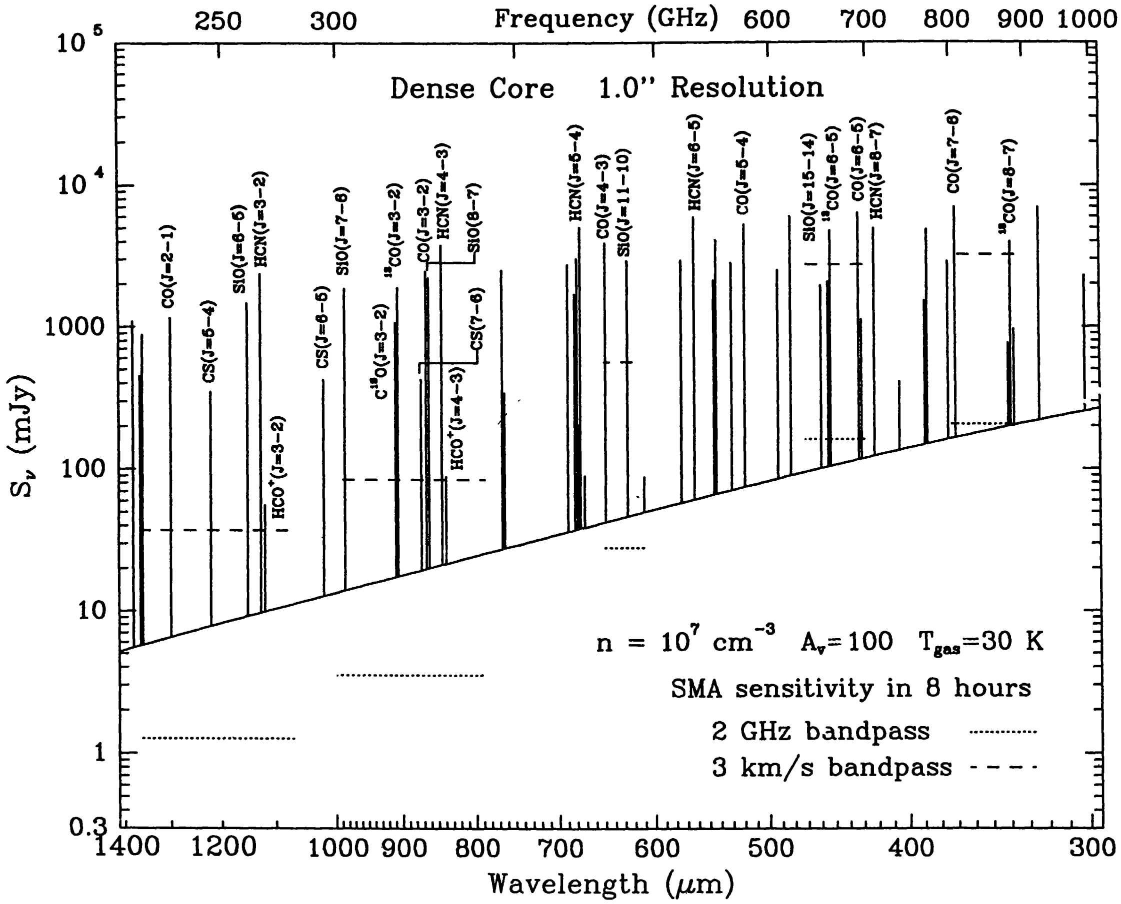

Fig. 1.— Spectrum of a dense cloud core, as observed by the SMA. Note that quite a number of lines can be imaged in a standard 8-hour track. As receiver performances improve, even more lines will be imaged. These calculations were made by Mark Wolfire.

through the atmosphere. This technique, first proposed by Foy & Labeyrie (1985), has been developed both in the military and academic sectors. By sensing and correcting for the distortions in the incoming wavefront, diffraction limited performance might be achieved with ground-based instruments. Groups in New Mexico, Illinois, Livermore, and many other places are actively pursuing these systems.

3.2. VLA

At the VLA, a number of improvements have taken place or are being planned. For example, the new 7 mm receivers funded by México, have allowed a whole new wavelength band to be attacked. Until the SMA, MMA, and LMSA are built, 7 mm operations at the VLA may be the most sensitive means to examine the dust at sub arcsecond resolution. There are also plans to broaden the instantaneous bandwidth which is processed by the VLA. Currently only 100 MHz is analyzed at a time. This limitation is imposed by the waveguide system at the VLA, and when that is replaced by an optical fiber system, at least an order of magnitude improvement in bandwidth can be expected. This will mean a lot for sensitive continuum measurements.

3.3. Expansion Projects

For interferometers, a very efficient way to upgrade is to add more elements, which will both improve the speed and the collecting area. All the millimeter wavelength arrays are adding more elements: BIMA from 6 elements to 11 elements, OVRO from 4 elements to 6 elements, NMA from 5 elements to 6 elements, IRAM from 3 to 4 elements. Even the SMA, which is under construction, is also working on expansion plans. The advantage is obvious because the speed scales with the total number of baselines.

4. KEY PROBLEMS

It is always difficult to predict what will be the next topics which will dominate any field. The first topic highlighted in this conference, circumstellar disks, was certainly predicted by the theoreticians. However, the second topic, outflows, was completely unexpected. Note that the circumstellar disks, predicted, continue to be difficult to detect. The ubiquitous molecular outflows and jets, unpredicted, continue to be difficult to explain. Is it that theoreticians would not or could not explain the observations? No, the answer is that this field has been driven on the observational end by technological developments which have been difficult and expensive. Because of cost, all of the new generation of instruments have been designed to take on a multitude of problems, rather than being specifically targeted. Moreover, heretofore, the sensitivity and resolution of the data were simply not good enough to constrain the models.

But, the time has come for better data. Further, the theories have become increasingly sophisticated with details and sizescales which may actually be observable. Here are some topics which may become tractable.

4.1. Circumstellar Disks

A number of talks and papers at this conference presented evidence for the existence of disklike structures. However, very few candidates, if any, possess all the features which should accompany a "real" disk: a highly flattened structure, gravitationally bound motions, density and temperature structures which are consistent with a concentration of matter toward the center, and an alignment of kinematical and morphological axes of

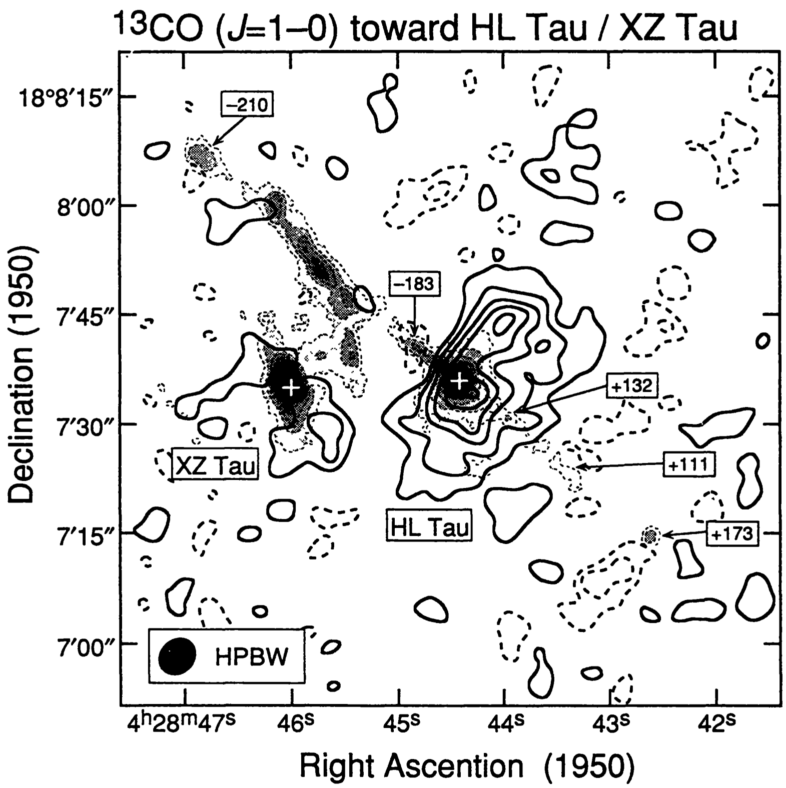

Fig. 2.— (a) Observed ^{13}CO emission towards HL-Tau from Hayashi et al.(1993). OVRO and IRAM have confirmed these observations.

symmetry which would be consistent with contraction models. For example, the HST images of Orion showed the projection of circumstellar clouds called "proplyds" against the optical nebula (see O'Dell 1995 in these Proceedings). However, there is no certainty that these are flattened structures rather than spheroidal structures, especially in the absence of kinematical information. The observed excess radiation in the submillimeter wavelengths toward some candidates have been interpreted as circumstellar disks. However, with present telescopes, none of this excess radiation has been spatially resolved. Hence whether these are disks or clouds, and whether they are circumstellar or interstellar, remain open questions. If circumstellar structures can be resolved which show the excess submillimeter emission, while the central cores account for the bulk of the near and mid infrared, we would have a better case. In this regard, the 7 mm continuum observations from the VLA may be the most powerful method at the moment to image the circumstellar dust emission at sub arcsecond scales. Finally, perhaps the best examples of circumstellar disks are the millimeter wave interferometric maps of sources like HL-Tau (see Figures 2a and 2b [Plate 4]; Hayashi et al. 1993; Sargent & Beckwith 1991). Here, three separate groups have imaged HL-Tau in ^{13}CO. Everyone agree that there are systematic motions. However, whether rotation, infall, or outflow, dominates in this region, is not clear. Moreover, the observed morphology, although elongated, is not highly flattened. The key to progress in this topic, must be higher sensitivity and higher angular resolution. Actually resolving the kinematics in the cold disks would be a top priority with the next generation of instruments.

4.2. Driving Sources

In the past decade, jetlike structures (e.g. Figure 3) have become the most convincing means to identify the exciting sources of outflows. In crowded fields, the mere presence of a compact infrared or radio continuum object, is not sufficient for the purpose of identifying the driving source. This is due to the fact that outflows may be a pre-main-sequence phenomenon, where the central source is not yet luminous and may still be very faint. Hence other supporting information such as jetlike structures, localized heating, enhanced linewidths, are needed. The key questions which remain unanswered are: what mechanism serves to focus the jet, how does the jet drive the outflow, and what is the relationship between outflow and infall. Theories from the Shu school of thought, and others, would argue for a unified approach where all of these phenomena are manifestations of the same event. There is general agreement that the accretion process is ultimately responsible for the outflow. Furthermore, the outflow is probably centrifugally driven by the coupling between the central star and the surrounding disk. Just exactly how this is accomplished is of course not yet observed, and may remain unresolvable even with the next generation of instruments. All of the action will be at a few stellar radii, which is on the order of $10^{-4\prime\prime}$ at 100 pc. Nevertheless there is hope that we will begin to see the disk structures surrounding the jets. With better instruments which will be sensitive to the faint dust emission from circumstellar disks, and with sufficient resolving power to see 10 AU structures (0.1″ at 100 pc), we might be able to tell whether there are material perpendicular to the outflow axis. If kinematics can be detected at this angular scale, one might ask whether infall will predominantly hit the disk, as predicted by theory, to be followed by inflow along the disk. On somewhat larger scales, the details of how jets interact with their environments are just beginning to be studied. The key is in finding the right atomic and molecular lines to study the chemistry of shocks. The studies of the optical lines of [OI], [SII], and others, have been enormously successful in studying shocks associated with HH objects. The v=1–0 S(1) line of H_2 has also been an invaluable marker for shocks. In regions of high extinction, millimeter wave interferometry of HCO+, SiO, and other molecules, have also been successful in studying the shocks. These studies will only become more important with increasing sensitivity. High resolution studies of the interaction zones, where jets collide with the ambient matter, may provide the clues as to how the stellar jets may drive the molecular outflows on a much larger scale.

4.3. Infall

After a decade where both observers and theoreticians gave up on the use of line profiles to detect infall signatures, there has been a revival of late on this technique. Early work in the 1980's dealt with the self-reversal profiles in CO and HCO+. There were difficulties associated with the large optical depths in the line. First, high opacities meant terrible radiative transfer effects along the line of sight. Second, since the opacity is high, the transition is sensitive to all the material along the line of sight. Thus, multiple velocity features superposed on the sky, plus molecular outflows, greatly confused any interpretation of infall. With the increased sensitivity achieved in the last few years, high spectral resolutions can be used to study the narrow lines of optically thin molecules in simple isolated clouds. As computed by Anglada et al. (1987), and then later by Zhou (1992),

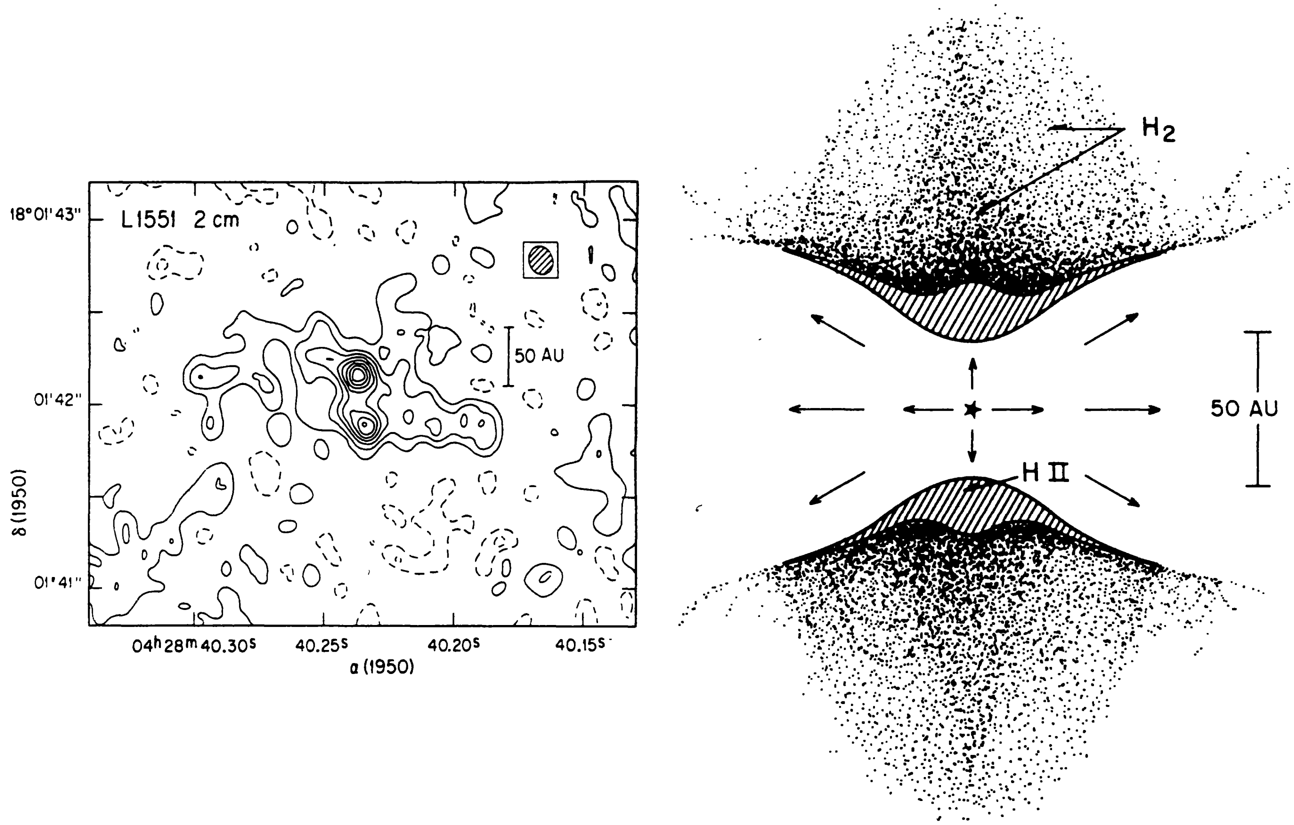

Fig. 3.— *Left.* 2 cm Continuum map of L1551 radio jet from Rodríguez et al. (1986). *Right.* Model of the inner region of the jet which is proposed to be confined by a dusty disk. The dust emission from this disk has been detected, although not imaged, by the CSO-JCMT interferometer at mm wavelengths.

line profiles in simple cloud cores will show the right asymmetries with sufficient spatial resolution. This seems to have been borne out by the observations in a number of cases now (e.g. Figure 4). Optically thin emission can be detected which shows redshifted emission in the foreground and blueshifted emission in the background, as is consistent with contraction. A particularly striking example, the HH1-2 system is discussed by Torrelles, Gómez, & Anglada (1995) in these Proceedings.

The attack on this problem in the next few years should be in the definition of the "profile" of the collapse. One needs to see the run in density and temperature with decreasing radius, the disposition of the angular momentum and possible spin-up motions as you approach the inner core, and finally the formation of a disk in the center. The availability of higher angular resolution is very important for these studies since the expected magnitude of the motions for the low mass cloud cores remains small until you get close enough to the center. Whereas existing millimeter arrays can already detect some of these signatures, the next generation of millimeter arrays will be able to provide a sufficiently large number of pixels on the collapse region. This will enable much more detailed tests of contraction models. In addition, the higher sensitivity will mean the possibility of using molecules of high excitation and low abundance, which will sample the inner cores of the collapse.

4.4. Planets

Direct detection of planets in extrasolar systems will be difficult. First of all, the sizescale of planets are too small to be resolved. Secondly, the brightness of planets as compared to the central star is perhaps a factor of 10^4 down. With the development of adaptive optics, it may be possible to see nearby planetary systems. As proposed by Angel et al. (1995), and computed by Sandler & Stahl (1995), a planet in a nearby system might be detectable if sufficient angular resolution can be achieved in the optical. There is also a good indirect way to

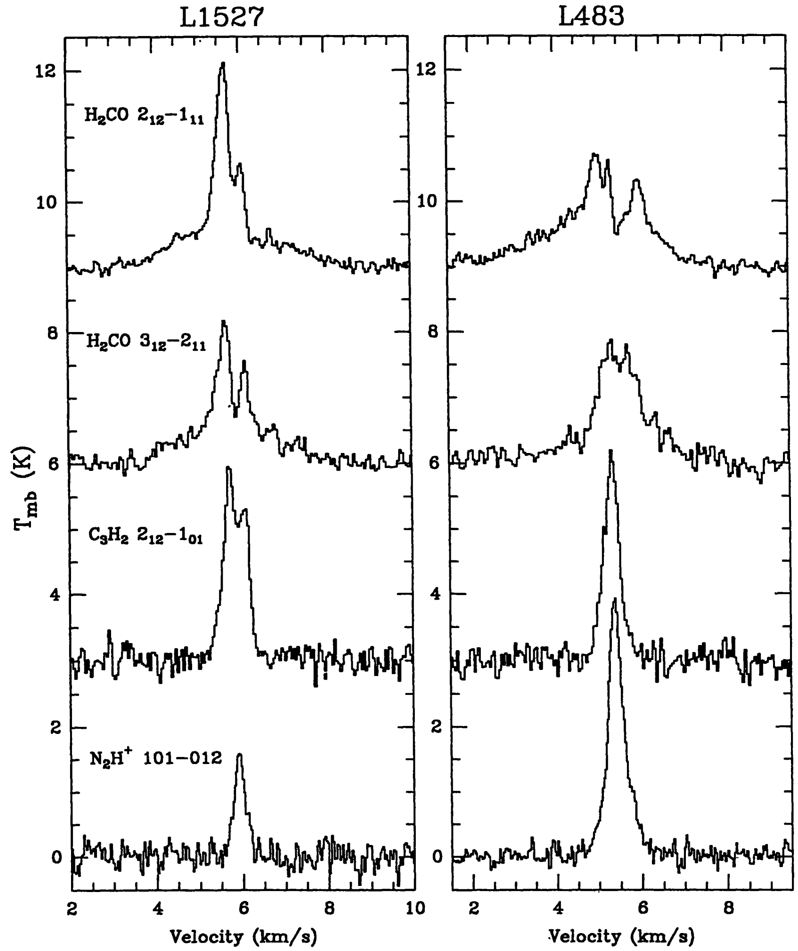

Fig. 4.— Spectra of a number of molecular transitions towards infall candidates L1527 and L483. Note the double-peaked profiles with the redshifted features being weaker than the blueshifted features, as predicted by infall models (Myers et al. 1995).

detect the planet, if a circumstellar disk is still in place. Calculations have shown that a planet or protoplanet will drive the formation of a gap because of tidal forces. Examples of this phenomenon were seen in the fly-by missions to Saturn, where the satellites which "shepherd" the gaps in Saturn's rings were detected. The area of the gap would be about 10^4 times greater than the projected area of the planet itself. There is therefore a possibility to see the gap in the circumstellar disk. With angular resolutions on the order of $0.01''$, such gaps may be directly imaged. A number of groups have tried to argue in favor of the detection of a gap or a hole in a disk by modeling the spectral energy distribution from the star (Mathieu et al. 1991; Marsh & Mahoney 1992, 1993). The idea is that a part of the disk is missing, so that some of the disk emission will be missing. In particular, if the gap or hole is towards the middle, the warmer dust emission, principally in the mid-IR, will be missing. The problem with such an interpretation is that the data to be fitted is a single spectral energy distribution from an unresolved object. Although there may be many points on this spectrum, they are not "independent" in the sense that they are not very sensitive to many of the parameters in the model. It is in fact difficult to distinguish between models with a hole or a gap in the disk and models where the dust opacity is sufficiently large to affect the perceived temperature distribution in the disk (Boss & Yorke 1993). This problem is difficult to solve until better angular resolution is achieved with the next generation of interferometers. If the disk can be resolved, then dust opacity distributions as a function of radius can be estimated even in the case where the gap itself is not resolved. With a known dust opacity distribution, whether the deficit in the mid-IR is due to a temperature or a column density effect, can be sorted out.

4.5. Protoplanetary Disks

If planets could not be detected directly, and if planets could not be detected indirectly via the gaps in the disks, everyone will still be very excited to be able to image the protoplanetary disks in a spectral line. The reason is that then the kinematics, excitation in terms of density and temperature, and the masses can be determined. Gómez & D'Alessio (1995) in these Proceedings have done the calculations for the likelihood of detecting protoplanetary disks. Their models show that whereas all existing interferometers will have a difficult time in detecting such objects, the next generation of millimeter and submillimeter wavelength interferometers will be able to resolve them with good sensitivity.

4.6. Magnetic Fields

Heroic efforts have been made in the past decade on studying the magnetic fields in the interstellar medium. The principal method has been to use the Zeeman effect for measuring the magnitude of the magnetic field (e.g. Heiles 1988; Goodman & Heiles 1994; Figure 5), and to use polarization studies in the optical and infrared for measuring the projected field directions. In the last few years, dust polarization studies in the far-IR, using the KAO, have been very successful in defining field directions in molecular clouds (e.g. Hildebrand et al. 1993). The idea is that the dust emission at these wavelengths should be optically thin so that magnetic field orientations are directly measured, in contrast to polarizations due to reflection or scattering. Polarization studies in the submillimeter at arc-second level can be very interesting for probing the magnetic field structures in the putative circumstellar disks. In particular, for the central parts of disks where winds are driven, the orientation and morphology of the magnetic fields are very important parameters to any of the theoretical models. Dust emission at different temperatures will peak at different wavelengths. Hence the dust polarizations at different wavelengths may tell us the magnetic field structures at different locations within the disks.

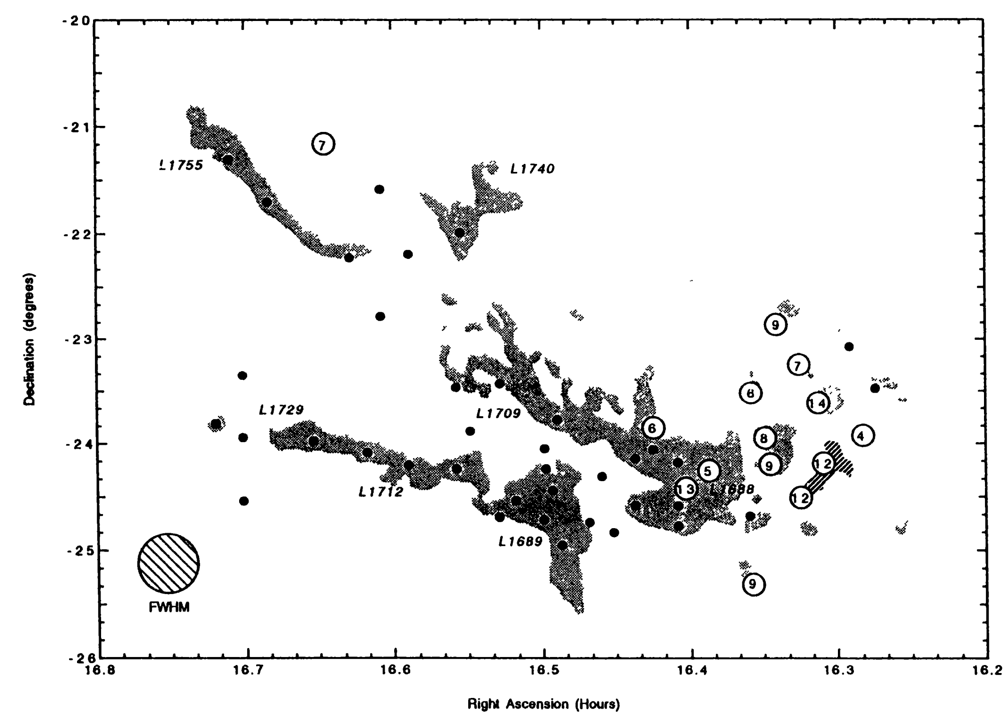

Fig. 5.— Zeeman measurements of HI towards Ophiuchus Dark Cloud Complex (Goodman & Heiles 1994). The open circles show the measured B field in μG, while the black dots show upper limits.

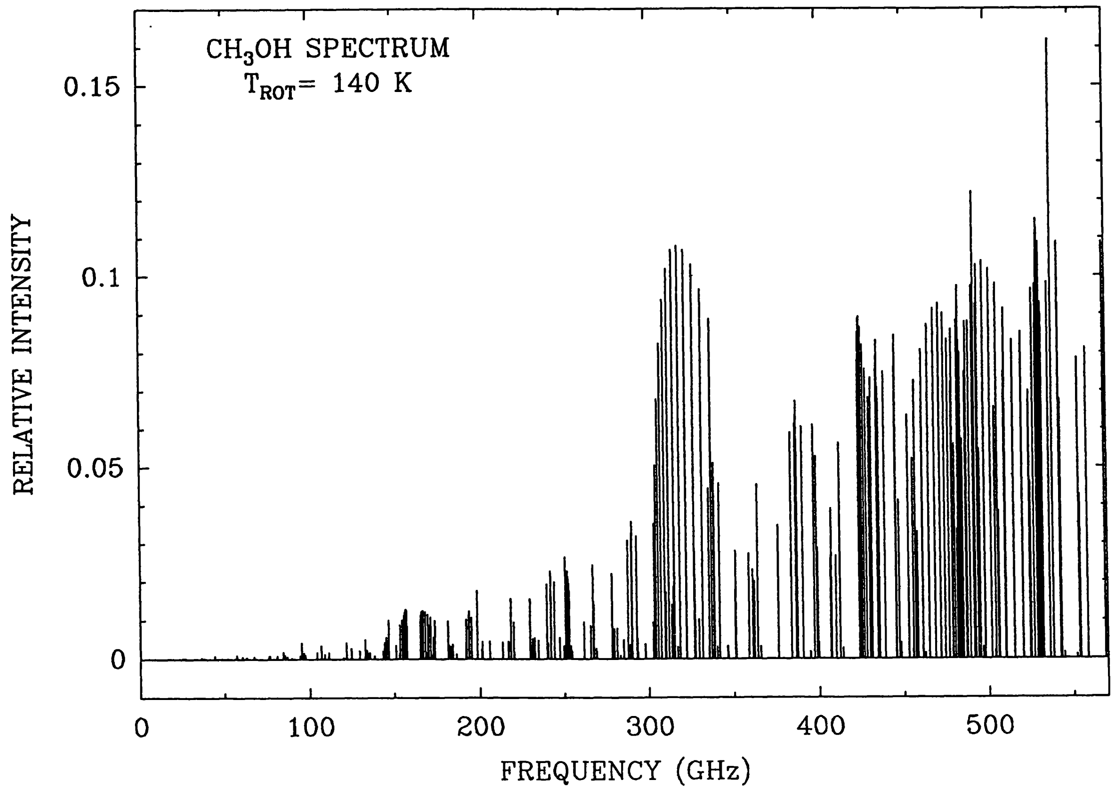

Fig. 6.— The relative intensities of the many CH_3OH lines at the submillimeter wavelengths at a temperature of 140K. These calculations were made by Karl Menten. The "forest" of lines continues above 500 GHz. The peak of this distribution will shift towards the higher frequencies at higher temperatures.

5. FUTURE DIRECTIONS

It would be presumptuous to predict where our field will head in the next decade. However, it is easy to see where the technical developments appear to be heading. The drive to higher angular resolution is taking place across the entire spectrum. Whether it is adaptive optics, space borne observatories, or ground based interferometers, the push is to get well under an arc second in angular resolution. Larger collecting areas are also being planned all across the spectrum. We can expect enhancement in sensitivities by at least an order of magnitude in almost every band.

The opening up of new parameter space, such as the submillimeter window, will be enormously important, because the bulk of the interstellar medium is cool enough that the peak of the spectral energy distribution is in the submillimeter and far-IR. We expect problems such as planet formation, disk formation, and dust emission, will see genuine progress. The submillimeter window will be a difficult one to work with. Even at high mountain tops such as Mauna Kea, excellent conditions with less than 1 mm of precipitable water vapor, may occur no more than 25% of the time. Furthermore, phase stability that will be required in order to have resolutions on the order of 0.1″, will be difficult to achieve. One may well ask why go through all this trouble. Figure 6 is a plot of the methanol spectrum as a function of frequency at a temperature of 140 K. Note the tremendous growth of lines as we head above 100 GHz. It is this "forest" of lines at the higher frequencies which holds the promise for this window. As has been promised so often, the best is yet to come.

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SUMMARY OF CONFERENCE

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RESUMEN

En la primera parte de este artículo se resumen algunos de los temas tratados en el congreso sobre "Discos circunestelares, flujos y formación estelar." En la segunda parte, se presenta una revisión de los esquemas de unificación que se han sugerido en este campo de investigación. Por último, en la tercera parte, se comentan diferentes perspectivas para la investigación futura.

ABSTRACT

The first part of this article summarizes some selected themes discerned among the papers presented at the conference on "Circumstellar Disks, Outflows, and Star Formation." The second part presents a review of the unification schemes suggested for this field. The third part comments on possible future directions.

Key words: **ISM: CIRCUMSTELLAR DISKS — ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

The organizing committee gave me the difficult task of summarizing this diverse and dynamic conference. I would like to begin by thanking the members of the local organizing committee (Jorge Cantó, Susana Lizano, José Torrelles, Vladimir Escalante, Luis Rodríguez, Paola D'Alessio, Will Henney, Jane Arthur) for the wonderful job they did in bringing together a most rewarding meeting. The students (Anabel Arrieta, Javier Ballesteros, Vladimir Avila, Rosa Izela Díaz, Alfredo Santillán) got every slide right-side up and handled each of our other problems with equal aplomb. Finally, no conference – and certainly not one with as much logistical complexity as this one – can succeed without the assistance of capable administrative helpers (Lila Perrilliat, Elizabeth Themsel, Josefa Soto, Reynaldo Hernández); this staff deserves our sincere gratitude and applause.

The title of this conference is "Circumstellar Disks, Outflows, and Star Formation." The most exciting example of star formation I personally witnessed at this meeting was the appearance of a bright new constellation of young Latin astronomers (YLA). Their acronym should not be confused with the VLA, where they can often be found to be working. As someone who has been involved in trying to promote astronomy in Taiwan, I have been impressed by the example of how quickly Latin astronomers, once organized by a few visionary leaders, have been able to surge to the forefront of our field. I have been especially encouraged by the fact that YLAs seem to have formed by both the cluster and isolated mode. May their groups (I, II, III) grow by accretion!

The scheme for this review is as follows. First, I shall summarize some common themes that I detected among the papers dealing with the three nominal topics of this conference – in permutted order: star formation, disks (and envelopes), and outflows (and jets). The time allotted does not permit me, as much as I would like, to do justice to all the papers – invited and contributed – presented at this fertile meeting. If I leave out your favorite paper, it is not because I found it to be less interesting, but merely that it did not seem to fall within the categories that I selected for summary. (I may also simply have missed seeing the connection to the stated themes.) Second, as light entertainment preceding the banquet, I will offer some revisionist history concerning unification schemes in our subject. Third, I will make some brief comments concerning possible future directions for the field.

2. STAR FORMATION

2.1. High-Mass Stars

One distinct impression made upon me at this conference is that the formation of high-mass stars (in compact groups and clusters) really does seem different from the case of (isolated) low-mass star formation. As discussed in the papers by Walmsley and by Olmi et al., the molecular cloud cores that give rise to high-mass stars are denser, warmer, and more massive. There also appears to be a much greater amount of material involved in the (inside-out) gravitational collapse of these cores (Wilner et al.), and a much greater amount of material swept up or entrained in the outflows (Cesaroni et al., Shepherd & Churchwell, Tafalla et al.). The search for radio sources near the positions of water masers may provide a frutiful technique for finding the youngest known high-mass protostars (cf. the reviews of Walmsley and Elitzur).

Newly formed stars of high mass play a much greater role in sculpting their natal cloud environment, perhaps helping to create the (filamentary) conditions conducive for the formation of further generations of stars (Wiseman & Ho). We used to say that high-mass stars did "greater damage to their environment," but damaging the environment is not politically correct, so we welcome the more benign image of "sculpting the environment."

High-mass stars also release many more ionizing photons than low-mass stars. The photoevaporative power of this radiation plays a central role in recent theoretical models of cometary H II regions (see the VLA observations of Gómez et al. that suggest a champagne-flow origin for two of these objects), compact H II regions (cf. the review of Lizano on $\sim$ 0.1 pc photoionization structures created by mass-loaded stellar winds), ultracompact H II regions (cf. the review of Yorke on $\sim$ 0.01 pc structures created by photoevaporating circumstellar disks around O and B stars; see also the observational attempts to detect the distinctive signatures of such regions by Kurtz et al.), and protoplanetary disks ("proplyds") of low-mass stars lit up by the photoionization and photoevaporation created by external illumination by a nearby O star (cf. the beautiful images presented by O'Dell, Bally, and McCaughren).

The mass-loss $\dot{M}$ induced by the last mechanism appears to be a surprisingly uniform $10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, which corresponds to a total removal of mass, $\Delta M = \dot{M}\Delta t \sim 0.1\ M_\odot$, over the typical lifetime $\Delta t \sim 10^6$ yr of a compact group of OB stars. This ΔM is an order of magnitude larger than the mass of a classical "minimum solar nebula." Such a rapid loss of gas would have profound implications for the formation of giant planets, if our solar system was born in a star-forming region characteristic of the Trapezium stars in the Orion nebula. The theoretical paper by Franco et al. carried this general line of thought to its logical extreme, ascribing to photoevaporation by high-mass stars the ultimate limitation of the overall star-forming capacity of giant molecular clouds.

2.2. Intermediate-Mass Stars

At this conference, the main issue discussed in connection with YSOs of intermediate mass appeared to be the controversy over the proper interpretation for the infrared excesses associated with Herbig Ae/Be stars. I used to think of the disk interpretation as the UMass school of thought and the envelope interpretation as the CfA school of thought, but there appears to have been so much brain exchange between those two institutions recently that those labels may be somewhat misleading. Adding to the confusion is the possibility of source confusion – infrared excesses may have been misidentified in many cases because of the large beams and the crowded conditions in which most Herbig Ae/Be stars are apparently born (see the review of Evans). The search for millimeter- and submillimeter-wave excesses has not clarified the situation (at least, not for me). Single-dish experiments at 0.35 and 1.3 mm by Mannings appear to justify the assertion that Herbig Ae/Be stars do have long-wavelength excesses, whereas millimeter-wave interferometry experiments at 2.73 mm by Di Francesco et al. seem to negate this conclusion. Interferometry at the greater sensitivity levels of submillimeter-wave measurements may be needed to resolve this issue. Complete SED fitting (Lorenzetti et al., Miroshoichenko et al.) may also help.

2.3. Low-Mass Stars

Infall along the equatorial regions occurring simultaneously in the presence of ouflow along the poles has, in my opinion, been definitively detected in the case of HL Tau (Sargent in her Conference talk). Cabrit et al. in their paper offer a different explanation, but it does not seem to this theorist that the slight differences in the Owens Valley, Nobeyama, and Plateau de Bure maps justify a complete reversal of the previous interpretation given by Hayashi, Ohashi, & Miyama. To explain the kinematic maps in terms of a molecular outflow requires (1) an unrealistically high level of turbulent entrainment from the surrounding disk, and (2) accidental levels of entrained material that just happen to mimic both the velocity and density fields expected for gravitational infall. Infall (through a pseudodisk) seems a simpler and more natural explanation, but in arriving at this conclusion, I must admit to being influenced by the fact that the flattened-infall point of view was predicted theoretically, *specifically for this source*, in advance of the actual observations (see the review of Galli).

Another trend fixed at this conference appears to be the usage of the terminology "Class 0." Although I belong to the group that believes a "Class 0" source to be physically just an extreme version of a "Class I" source, I have come to agree that the nomenclature "Class 0" does serve a useful purpose in succinctly bringing to mind a certain coldness of the spectral energy distribution (SED) and a high typical degree of collimation of the accompanying molecular outflow (see the papers by Bachiller and Dutrey et al.). Together with Mike Simon, I do wish that standard typography might be introduced to print "0" as a roman numeral. (I balk, however, at introducing minus signs in front of roman numerals.) That the SED classes do correspond generally to a physical distinction (and not just a difference, say, of viewing angle) appears established by Eiroa's correlation of the amount of "veiling" of the stellar photospheres with the class type. The proposal by Saracceno to use the $L_{\rm bol}$ versus $F_{\rm mm}$ diagram to sort the evolutionary status of YSOs also has as its basis the viewpoint that the envelopes of Class I sources are not simply static re-radiators of the stellar photons, but are dynamically infalling and contribute to the accretion luminosity of the system (and to the veiling of the stellar photosphere).

I also discerned at this conference – in the work of Whitney, Galli, Menard, Bjorkman, and Ageorges – an increasing use of polarization maps to diagnose the envelopes (and pseudodisks) of embedded sources. It should be noted that this method is primarily sensitive to the size and opening angle of the *holes* in the envelopes (created by outflows or evacuation of the polar regions because of a flattened infall); therefore, polarization maps are primarily a diagnostic of where the matter *isn't* rather than where the matter *is*. As such, they constitute a fine complement to the more traditional method of using far-infrared intensity maps to determine the radial density distribution $\rho(r)$ of dust envelopes (Harvey et al.). The latter provides a more model-independent technique than does SED fitting for determining $\rho(r)$.

Millimeter-wave polarization maps via interferometric arrays promise to give a revolutionary new way to study magnetic fields in dense regions (Akeson et al.). When Telemachos Mouschovias is not around, people tend to forget that **B** really is dynamically important. In a new chemical study, Halmich et al. determine that the electron fraction $x_e \approx 10^{-8}$ in two dense cloud environments where $n_{H_2} \approx 10^6$ cm^{-3}. This value compares well with the formula $x_e = 10^{-7}(n_{H_2}/10^4 \text{ cm}^{-3})^{-1/2}$ often adopted by theorists to study the role of ambipolar diffusion in the contraction of molecular cloud cores and the goodness of magnetic coupling in the subsequent dynamical collapse. Montmerle et al. point out that the x-rays of embedded low-mass YSOs increase the ionization levels associated with cosmic-rays alone. (The ionization rate due to cosmic rays is assumed itself in the study of Halmich et al. to be considerably enhanced over the conventional value $\zeta = 10^{-17}$ s^{-1}.) Montmerle et al. resurrect an idea due to Norman and Silk that such x-rays may self-regulate the rate of (low-mass) star formation in molecular clouds. The determination of x_e in different star-forming environments constitutes a method to check this important idea empirically.

2.4. Binaries and Multiple Star Formation

In Boss's review, he emphasized that initial radial density profiles flatter than $\rho \propto r^{-2}$ are needed to get fragmentation of a molecular cloud core during the dynamical phase of collapse (before protostar or disk formation). I would merely remind the reader that the coefficient in front of the dependence in r matters too. Some of the initial states used in the numerical simulations are too far out of virial equilibrium to be realistic. One has to question if the evolution proceeds so quickly after $t = 0$, what was the evolution like before $t = 0$? Nevertheless, the basic point is valid that the formation of binary and multiple star requires a departure in the standard thinking that produces a single star plus a circumstellar disk. The numerical simulations provide suggestive starting points for alternative thinking.

An interesting idea advanced at this conference is the update by Bonnell et al. of the proposal by Abt and Levy that binary-star formation is a bimodal process: binaries with separations less than 30 AU form (mostly) by disk fragmentation, whereas binaries with separations greater than 30 AU form (mostly) by capture. While I personally also like the idea of disk fragmentation to form the shorter-period binaries, I suspect that the capture scenario for the longer-period binaries has already been ruled out by observations. In particular, Prato & Simon and Moneti et al. present papers at this conference that demonstrate *both* stars in T Tauri binaries show T Tauri characteristics. This demonstration applies to the binaries associated with the Taurus dark cloud, where weak-lined T Tauri stars (WTTSs) without optical/infrared disk signatures outnumber classical T Tauri stars (CTTSs) with optical/infrared disk signatures, and where independent star-forming regions in this cloud are fairly well separated (as well as possess small random motions relative to one another). Thus, the chances for one star plus a disk to capture another with a disk is very small within the allotted time scales (a few times 10^6 yr, see the review of Strom), when both stars are likely to have disks. This result agrees with the detailed theoretical calculations made in Eve Ostriker's Ph.D. thesis, where it is concluded that the binary-capture cross-section for conventional circumstellar disks is quite small.

For the wider separations, instead of capture, it may be more fruitful to contemplate the coherent magnetized collapse of massive regions into large flattened structures (self-gravitating pseudo-disks) that may further fragment into clusters, multiples, and binaries (Nakamura et al.). Inasmuch as the pre-collapse state of such regions are likely to be supported at least in part by magnetohydrodynamic turbulence, it would be important to learn more about the latter subject (Nordlund & Padoan).

3. DISKS (AND ENVELOPES)

Resolved images from millimeter- and submilliter-wave interferometry tentatively confirm that centrifugal disks are generally small, $\sim 10^2$ AU (Carlstrom), except when they are around binary systems (Sargent, describing the work of herself and Koerner; see also Monin). Circumsteller disks are ubiquitous (all young stars have them), and mean disk lifetimes can be deduced from the statistics garnered from young stellar clusters (Strom, McCaughren). On the other hand, what used to be modeled in SEDs as "disk," with $T \propto \varpi^{-q}$, may be contaminated by material off the equatorial plane (Natta, Cantó). For "pure" disks (reprocessing or accretion), we should adopt a temperature power-law index $q = 3/4$. There are, however, two caveats to the rule $q = 3/4$: not during an FU Orionis outburst (Kenyon, Bell), and not if gravitational instability provides the principal accretion mechanism (Bodenheimer).

The modeling of realistic disk atmospheres is getting very sophisticated (Calvet, D'Alessio et al.), although general statements can still be profitably made concerning the contribution to protostellar SEDs from spherical envelopes (Ivezic & Elitzur). Boundary-layer theory is improving rapidly, but controversial points still remain concerning the proper form of the inner thermal boundary condition (Popham, Lioure). Classical boundary layers are probably present in Fu Orionis stars, but they may be replaced by magnetospheric-accretion hot-spots in T Tauri stars (Edwards, Ostriker & Shu). Some SEDs of T Tauri stars show evidence of the kinds of inner holes that might arise as a byproduct of magnetospheric accretion (Hillenbrand). A significant development in this regard is the discovery by Carr et al. (see also the review of Najita) that Brackett γ may constitute a good diagnostic line for magnetospheric accretion, opening the the way to the infrared spectroscopic investigation of this phenomenon in embedded sources in a manner analogous to that carried out so successfully by Hartmann, Hewett & Calvet for the case of optically revealed sources. It would be good to know whether there are systematic differences between embedded and revealed sources caused, for example, by differences in the disk accretion rates $\dot{M}_D$.

The theory of disk instabilities has also shown great recent advances. FU Orionis outbursts, modeled as thermal instabilities in the inner accretion disk, set important constraints on the viscosity parameter α (Bell). The fine-tuning needed for this parameter to obtain good light-curve fits for different sources may indicate, however, some difficulties with the details of the α formalism. In particular, as directly calculated by Bodenheimer (in collaborative work with Laughlin) and by Kikuchi & Miyama (for the disk formed from the collapse of a rotating singular isothermal sphere), gravitational instabilities almost certainly coexist with any thermal instabilities in the early stages of the development of a star/disk system. Whether gravitational instabilities yield only angular momentum and mass transport, or also lead to disk fragmentation, is controversial (Adams). Numerical simulations have not settled this point, because the saturation amplitude of nonlinear spiral modes (which depends on a balance of the growth of the instability and the physical damping inherent in the system) in the presence of continuing infall (which tends to destabilize the disk) has not been convincingly followed to the requisite accuracy and duration in any simulation carried out to date. My own guess is that if disk fragmentation is to be successful, it must happen fairly early (when the doubling time for the accumulated mass of any disk is small), and that the subsequent growth to two (or more) stellar-sized companions occurs via continued infall from a common envelope onto two circumstellar disks (that interact gravitationally with each other and with their central stars) and, also, a circumbinary disk.

An important topic largely overlooked at this conference is the issue of planet formation from circumstellar disks, although in his forecast of the observational riches that lie in our future, Ho did discuss the observability of gaps that might be opened in the disk by embedded planets of the kind first predicted by Lin & Papaloizou. Good news in that regard came from the theoretical calculations of Takeuchi & Miyama, who showed that embedded bodies (stars or planets) can open gaps wider than previously calculated because of the resonant excitation and propagation of spiral density waves. I would also remind the reader that the appearance of a massive planet like Jupiter in a low-mass disk can not only open a gap, but it can also hold back the inflow of material of the outer disk into the inner regions (if the outer disk is not too massive), which may then drain onto the central on a fairly short time scale (as in the calculations of Ruden & Lin). In such a situation, it may be more profitable to look for 10-AU (diameter) *holes*, rather than 1-AU gaps, with a fairly sharp edge to the hole beginning exterior to the ice-condensation point (needed in most planet accumulation theories to explain the formation of the cores of giant planets), where the nebular temperature $\sim$ 150 K. In this regard, WTTSs with mm-wave continuum emission might constitute inviting targets.

4. OUTFLOWS (AND JETS)

A central underlying theme in the parts of this conference that dealt with jets and outflows is the question (see the review by Reipurth, many contributed papers): Do the observed stellar jets drive molecular outflows, or are the jets simply the innermost parts of a less well-collimated wind, which constitutes the true driver? If a poll were taken today, the majority opinion would probably opt for jets as the only primary driver. My own opinion is that we should not rush to a premature judgment before all the evidence and all the arguments are in.

A related question is: What is the mass flux ratio $f = \dot{M}_w/\dot{M}_D$ carried in the jet or wind relative to disk accretion? A perusal of the papers presented at this conference yields a wide variety of empirical estimates: $f = 0.001 - 0.01$ from [O I] in CTTSs (Edwards, Hartigan et al.); $f = 0.01 - 0.1$ from optical emission lines in the HH 34, 37, 111 jets (Morse et al.); $f = 0.2 - 0.4$ from swept-up CO in NGC 2264G (Lada). Either different sources really show this variety, or the observers need to do better. To give them some motivation, I note that the "preferred theoretical model" to be discussed near the end of this article predicts $f \approx 1/3$ as a steady-state value. To the extent that CO outflows measure a time-integral or average of the phenomenon, the observational evidence seems marginally in accord with this prediction.

Do jets collimate hydrodynamically (Frank & Mellema, Wilkin & Stahler), or magnetohydrodynamically (Königl)? My own take on this question is that collimation provides the wrong initial focus. As Königl summarized in his review, in 1980 DeCampli already pointed out that the large values of $\dot{M}_w$ deduced for CTTSs, never mind the more powerful embedded drivers of bipolar outflows, eliminates the possibility of pure hydrodynamical models. To drive the requisite mass-loss rates thermally (as in a scaled-up solar wind) would produce much more x-ray emission than is observed for CTTSs. Thus, we are forced almost a priori to consider magnetohydrodynamical models. Nevertheless, I do not take the position that this stance eliminates the possibility for some hydrodynamical role in the collimation process. Contrary to common belief, realistic magnetohydrodynamical models cannot produce pencil-beam jets. To bring some or most of the streamlines in an initially uncollimated flow into a vertical position requires, by Newton's third law, those streamlines (or magnetic fields) to push against something. That something will almost always produce streamlines that try to emerge equatorially (as in the X-wind models described by Najita). The self-similar disk winds of Blandford and Payne described by Königl violate this dictum, but only at the expense of having the disk and its wind extend infinitely in the radial direction. If the disk were to come to an end at a finite radius, the last wind streamline would be forced by the pressure of the streamlines (and field lines) interior to it to bend over to an equatorial position. Thus, if optical jets are truly isolated pencil-beams, without a wider-angle wind counterpart, then one needs to invoke some hydrodynamical obstacle (flared disk, infalling envelope, flattened cloud core, interstellar toroid, ...) to eliminate the more-or-less equatorially traveling streamlines.

Many other intriguing questions on this general topic were also raised and addressed. Are the molecular lobes in bipolar outflows swept up or entrained from the ambient medium? How does entrainment work? Dyson sensibly proposes to address this difficult question, not by a priori theoretical calculation, but by empirical model fitting. Raga (as represented by Dyson) introduces a most intriguing possibility: the intermittent effect of a time-variable jet may generate something like a "second wind," that then sweeps up the ambient medium into the observed molecular lobes. Masson and Welch want to accomplish the same task with a wandering jet, but the experts seem divided on the latter issue. In the question and answer period, Dyson states that "he'd be surprised if jets didn't wander," while Mundt claims that "there's no observational evidence that jets ever wander."

Do CO outflows define shells? At one time, L1551 was cited as the classical example of a shell-like source (favoring the swept-up interpretation). But in a reassessment, Fridlund et al. find that the interior of the lobes is filled with CO gas moving at appreciably higher velocities than at its edges (favoring the entrainment picture). To be fair to the shell proponents, however, no one ever thought that the interiors of the shells would be completely empty. In any case, a study of the shell shape and distribution of molecular mass with velocity of some well-observed nearby bipolar outflow sources by Xie and Goldsmith finds that none of the existing theoretical models fits the data very well.

5. UNIFICATION SCHEMES

Now for some light entertainment, a biased review of unification schemes in this field. Joan Najita is probably cringing at the title of this section, since she feels that the word "unification" carries a lot of pompous baggage, best left to a certain brand of particle physicist. I tend to agree with her, but at this meeting, a number of speakers (Alan Boss and Paul Ho in particular) have referred to me as some kind of religious leader. Having pondered this development, I have come to the conclusion that if I must assume a religious mantle, I would like to be the head of the Unification Church. Henceforth, you may greet me as the Reverend Sun Moon Shu.

It was Safranov, I believe, who said that there are only two kinds of objects in the universe: spheres and disks. If he had attended this conference, he would probably have revised his assertion to there being only three kinds of objects in the universe: spheres, disks, and outflows.

Of these three kinds of objects, I would like Paul Ho to observe that two were anticipated by theorists. It was Pythagoras who first explained that the Earth, Sun, and Moon are spheres. (That's why in Ho's cartoon, I don't need to look – the Reverend Sun Moon Shu already knows that the Sun and Moon are spheres.) And it was Huygens who explained that the rings of Saturn, which were initially imagined by an observer (Galileo) to be ears on a planet, really formed a disk.

Outflows, however, came as a complete surprise discovery by observers of the stature of Herbig; Haro; Snell, Loren, and Plambeck; Rodríguez, Carral, Moran, and Ho; Mundt; and Reipurth. To give theorists their due, in the field of active galactic nuclei (AGN), Blandford and Rees predicted that there should be jets to power the lobes of extended radio sources before such jets were actually detected.

Because outflows are a relatively recently discovered phenomenon, it should not surprise us that the earliest unification schemes ignored them. The first unification scheme with modern merit was proposed by Laplace, who published the *nebular hypothesis* in 1796 that spheres (the Sun and planets) are born from disks.

To simplify calaculations, succeeding generations of theorists (Kelvin, Helmholtz, Henyey, Hayashi, Bodenheimer, Larson, Appenzeller, ...) considered gravitational contraction of a gas cloud to form the Sun (and other stars) in *spherical symmetry*. This program proved to be amazingly successful, leading to the eventual elucidation of the true energy sources of the stars as well as now-established concepts such as pre-main-sequence contraction tracks and the stellar birthline. Nevertheless, the program ignored the basic question of how to form a round ball if the original gas cloud rotates and contraction needs to occur over a large dynamic range (a factor of 10^6 if R shrinks from 10^4 AU, the size of a molecular cloud core, to 10^{-2} AU, the size of a T Tauri star).

The basic difficulty – the spin angular momentum problem – is posed by Kelvin's circulation theorem, which can be derived from Euler's equation for ideal gas dynamics:

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla\left(\frac{1}{2}|\mathbf{u}|^2\right) + (\nabla \times \mathbf{u}) \times \mathbf{u} = -\frac{1}{\rho}\nabla P - \nabla V,$$

where ρ, $\mathbf{u}$, and P are the fluid density, velocity, and pressure, and V is the gravitational potential. If P can be approximated as a function of ρ, $P = P(\rho)$, then the curl of the above equation produces Kelvin's circulation theorem:

$$\frac{\partial \omega}{\partial t} + \nabla \times (\omega \times \mathbf{u}) = 0,$$

where $\omega \equiv \nabla \times \mathbf{u}$ is the vorticity and equals twice the local angular rotation rate $\mathbf{\Omega}$ of the fluid if it were to be instantaneously frozen (i.e., forced to rotate rigidly). The integral form of Kelvin's circulation theorem can be written as (the preservation of spin angular momentum per unit mass):

$$\int_{A(t)} \omega \cdot \hat{\mathbf{n}}\, dA = \text{const},$$

where $A(t)$ is any area element that moves (or contracts) with the fluid. If this area is characteristically measured by πR^2, then Kelvin's circulation theorem states that the spin rate scales as $\Omega \propto R^{-2}$. If R contracts by a factor of 10^6, then we may expect the spin period $2\pi/\Omega$ to decrease by a factor of 10^{12}: from 10^6 yr, a typical value for a molecular cloud core, to 10^{-6} yr = 30 s, by the time the fluid is incorporated in a star. A T Tauri star rotating on its axis once every 30 s would have a rotation speed approaching the speed of light, so clearly something is wrong with this application of Kelvin's circulation theorem.

Notice that Kelvin's circulation theorem allows an arbitrarily complicated gravitational potential V; thus fragmentation into binaries and multiple stars does *not* constitute a solution for the *spin* (as distinct from the orbital) angular momentum problem. Moreover, any reasonable viscous torque (ignored in the above derivation) is proportional to $d\Omega/d\varpi$. Therefore, to transfer angular momentum outwards, the spin rate Ω has to increase inward, i.e., for a central star to lose angular momentum to a circumstellar disk viscously and gain mass from the same disk, the star has to rotate faster than the inner edge of the disk. This result implies that viscous transport through an accretion disk is also *not* a solution for the spin angular momentum problem of the *star* (although it is fine for the disk). Since Popham comes to a different conclusion in his presentation, I should elaborate a bit on our difference. If one has some mechanism that differentiates between the material of the star and the material of the disk, then one might imagine (as Popham does) that one could start with the star slowly rotating, while sticking a long tongue (extended boundary layer) of hot material, rotating at slower than Keplerian speeds, between the surface of the star and the accretion-disk proper that mediates a continuous outward transport of angular momentum. Star formation, however, presents us with a problem of the formation of both a star and a disk from the same rotating molecular cloud core. How does this material ever distinguish whether it belongs in a rapidly rotating disk or a slowly rotating star if we have available only a single source of viscosity? Some other agent seems necessary to perform the discrimination.

Another solution to the spin angular momentum problem was recognized and posed by Mestel and Spitzer in the 1950s and 1960s: magnetic braking (also ignored in the above derivation of Kelvin's circulation theorem). But the existence of a magnetic field $\mathbf{B}$ gives rise to its own difficulty: the magnetic flux problem.

The magnetic flux problem arises if the collapsing gas cloud is sufficiently electrically conducting as to warrant the approximation of field freezing. The equation of field freezing can be derived as follows. Faraday's law of induction states that

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}.$$

A conducting fluid tends to short out the electric field in the rest frame of the fluid of ions: $\mathbf{E}_i = 0$. A nonrelativistic Lorentz transformation relates $\mathbf{E}_i$ to the electric and magnetic fields in the laboratory frame: $\mathbf{E}_i = \mathbf{E} + \mathbf{u}_i \times \mathbf{B}/c$,where $\mathbf{u}_i$ is the ion fluid velocity. With $\mathbf{E}_i = 0$, we get $\mathbf{E} = \mathbf{B} \times \mathbf{u}_i/c$, which substituted into Faraday's law of induction yields the freezing of the magnetic field to the fluid of ions:

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{B} \times \mathbf{u}_i) = 0.$$

The similarity of the above equation with Kelvin's circulation theorem allows us to write the integral form of field freezing as (the preservation of magnetic flux):

$$\int_{A_i(t)} \mathbf{B} \cdot \hat{\mathbf{n}}\, dA = \text{const},$$

where $A_i(t)$ is an arbitrary area element that moves with the fluid of ions. Field freezing to the ions therefore implies that $B \propto R^{-2}$ if the ions contract similarly as the neutrals in the process of star formation. A reduction in R by a factor of 10^6 would then result in an increase in B by a factor of 10^{12}, i.e., B should increase from 3×10^{-5} G to 3×10^7 G in the contraction of a molecular cloud core to form a star. Since the highest fields attributed to pre-main-sequence stars measure at the kilogauss level, and not the tens of megagauss, clearly something is amiss in the above application of field freezing.

A partial solution to the magnetic flux problem was proposed by Mestel and Spitzer in 1956: ambipolar diffusion. Because molecular clouds are lightly ionized, there can be a slow drift of neutrals relative to ions and fields. Combining the two ideas of Mestel and Spitzer, Mouschovias proposed in the late 1970s a second unification scheme: Magnetic braking and ambipolar diffusion in the interstellar medium produce the entire range of single stars and binaries. Unfortunately, as Nakano and others soon pointed out, this unification scheme runs into its own difficulties. The actual ionization levels present in molecular clouds appear only low enough to allow ambipolar diffusion to play a significant role during the quasistatic contraction phase of molecular-cloud core evolution. This is the stage that magnetic braking can couple the rotation rate of the core to that of its envelope. However, once the core goes into dynamical collapse, both the magnetic flux and the spin angular momentum tend to be conserved, until very high densities are reached (in a pseudodisk or disk). In our numerical estimates above, we used as the initial Ω and B, the values determined for dense cores on the verge of collapse. Thus, we have already empirically factored in the effects of interstellar magnetic braking and ambipolar diffusion into our discussion, and we are still left with difficulties. Stated in a different way, too much fine-tuning would be required for gravitational collapse, spin angular momentum redistribution, and magnetic flux loss to keep exact pace with each other over the large dynamic range encountered in the transformation of an unstable molecular cloud core into a star. Finally, even if this fine-tuning could be accomplished (in another galaxy), we note that Mouschovias's scheme produces only spheres (a binary is just two spheres). Disks and outflows make no explicit appearance in his scheme.

A partial resolution of the difficulty is already hinted upon in the above discussion. An unstable molecular cloud core, slowly rotating because of magnetic braking in the previous quasistatic stage, undergoes dynamic (inside-out) collapse by a factor of about 10^2, from a 10^4 AU core onto a 10^2 AU centrifugal disk. The high angular-momentum material from the initially extended state does not fall directly onto a star whose radius, 10^{-2} AU, is smaller yet by another factor of 10^4. In this way, nature avoids the spectacle of a pre-main-sequence star spinning at the speed of light. Of course, this partial resolution leaves us with the problem of how does the (accretion) disk, and the central star that it feeds, deal with the remaining spin angular momentum problem. We have returned, therefore, to the starting point of Laplace.

This starting point sets the stage in the 1980s for a third unification scheme. Drawing on the work of Blandford and Payne for AGN disks, Pudritz & Norman and Königl propose that if the interstellar **B** is not lost from the disk, then a disk wind can be centrifugally driven by the poloidal fields threading the disk. A unified picture arises because the back reaction of this wind on the disk will torque down the matter in the disk and allow it to accrete onto the star, *even in the complete absence of any viscous transport mechanism.* This scheme is the first to have all three of the elements: star, disk, outflow.

There are, unfortunately, also a number of difficulties associated with this attractive proposal. Foremost among these difficulties is the calculation of Umebayashi & Nakano in 1988 that the disks in low-mass YSOs may be too insufficiently ionized in its midplane for the radial extent $\varpi = 0.1$ to 20 AU to retain any interstellar **B**. In an updated study, Stepinski at this conference confirms the same basic result. Even if the surface layers of the disk are sufficiently conducting, large inward drifts would be needed there to bend the field lines by enough to obtain magnetocentrifugal fling of the outermost layers into a disk wind. The large inward drift may make it problematical to keep the threaded fields from being swept to small radii (where the mechanism would then not look very different from the X-wind proposal discussed below). The remaining fields in the surface layers that might be sustained by dynamo action might be useful as a viscosity mechanism, but they are probably too weak to drive outflows. Finally, in a disk-wind scenario where the driving field lines attach only to the disk and not to the star, the central star does not become a sphere, i.e., its spin angular momentum problem is not solved by a pure *disk* wind.

An alternative 1980s' scheme for producing massive outflows was suggested by Hartmann & MacGregor and elaborated upon by Shu, Lizano, Ruden, & Najita (SLRN): mass loss from a magnetized protostar rotating at breakup speeds. In particular, SLRN added the ingredient of an adjoining accretion disk. The disk plays two roles: (1) to justify the assumption that a protostar spins at breakup, and (2) to provide a reason why the mass-loss rate has any particular value. In the SLRN theory, $\dot{M}_w = f\dot{M}_D$, with f estimated for the outflow source in HH7-11 on semi-empirical grounds to be ~ 0.4.

Unfortunately, this proposal itself has a problem: the central star is rotating at breakup and is therefore also not a sphere. Moreover, although the embedded drivers of most bipolar outflows are not observed directly (except possibly in x-rays), Edwards and her colleagues pointed out that revealed CTTSs rotate at about only a tenth of breakup, and yet they also satisfy a relationship of the form $\dot{M}_w = f\dot{M}_D$.

The spotlight then shifted to why CTTSs rotate as slowly as they do despite accreting material of high specific angular momentum from a surrounding disk. Onto the stage stepped Arieh Königl in 1991 with a brilliant suggestion: magnetospheric accretion as developed in the late 1970s by Ghosh & Lamb to model binary x-ray sources. Königl proposed that the stellar magnetic field of T Tauri stars may be strong enough to truncate the disk before it reaches the stellar surface, thereby preventing the accretion disk from spinning the central star to breakup. Unfortunately, although this basic suggestion has a lot of appeal, the detailed theory of Ghosh & Lamb has some dubious assumptions. Central among these is that the spindown torques on the star that counteract the spinup tendencies of the magnetospheric accretion in the Ghosh & Lamb model occur through lightly-loaded stellar field lines that thread the disk over an extended region of the disk. Although lightly-loaded field lines can carry electric current, $\mathbf{j_e} \propto \nabla \times \mathbf{B}$, they have difficulty supplying much torque. Indeed, such field lines in the case of the solar corona are usually modeled as *force-free*, with $\mathbf{j_e} \times \mathbf{B} = 0$. These field lines are therefore intrinsically incapable of exerting (much) torque. Stated another way, if such lightly-loaded field lines did exert torque comparable to those of the heavily loaded field lines that carry matter to the star, then the angular acceleration that the former would produce in the inertia-poor material tied to them would become impossibly large. Without the spindown torques of the outer field lines, the spinup problem for the central star is worsened (according to Ghosh & Lamb) by trunctating the disk before it reaches the surface of the star, because the specific angular momentum of the accreting gas is correspondingly higher.

Thinking about these difficulties and others led a group of us (Shu, Najita, Ostriker, Wilkin, Ruden, & Lizano) to realize last year that a stellar field strong enough to truncate the disk at R_x *automatically* has enough power to drive both funnel inflow and an X-wind outflow from a small X-region near the inner disk edge R_x. Moreover, contrary to previous expectations, we found that the funnel flow onto the star can supply its own magnetic torque that keeps the star slowly rotating (if $R_x \gg R_*$). This fourth unification scheme retains the strengths of the previous pictures while eliminating their weaknesses. To be more specific, in recent years theorists have converged on the view that outflows and jets probably require a basic driving mechanism that combines strong magnetic fields with rapid rotation. Centrifugal disks are attractive in that, by definition, they rotate at each radius as fast as possible consistent with equilibrium. Taken by themselves, however, they fail because they probably do not possess the requisite strong fields (at least, not the disks around low-mass YSOs). Rotating stars with outer convection zones are attractive in that we know empirically from direct and indirect measures that they possess strong surface fields (probably as a result of dynamo action). Taken by themselves, however, they fail because they do not rotate very quickly (at least, not the CTTSs). The fourth unification scheme combines the strong magnetic field of the star with the rapid rotation of the disk (at R_x) to drive both mass inflow and mass outflow. As a bonus of the process, the low rates of disk accretion $\dot{M}_D$ of CTTSs result in a relatively large ratio $R_x/R_* \sim 5$, and the star is regulated by the process to spin at a rate about a tenth of breakup. In other words, the star is a sphere. We have returned all the way back to Pythagoras. This is a great testament to the illusory nature of progress in theory.

The proposed mechanism corresponds to a magnetic braking of the star by the disk and its induced X-wind. We can now answer our earlier question: What constitutes the crucial difference that discriminates matter destined to form the star from matter belonging to the disk? Answer: The stellar matter is that part which generates (by internal processes in low-mass YSOs) a magnetic field strong enough to build a sphere out of a disk.

The details of the above theory have already been described in the presentations by Najita and Ostriker & Shu, so I will not repeat the arguments here. For the convenience of readers who do not have the time to work through the published papers, let me summarize the important reults that one can derive from conservation principles alone, without the need to rely on any detailed calculations. These general results hold as long as we have steady cold flow from virtually a single point at R_x, where the stellar flux (including both open and closed field lines) that interacts with the disk is trapped. The location of the disk edge is given by dimensional considerations as the Ghosh and Lamb law:

$$R_x = \Phi_{dx}^{-4/7} \left(\frac{\mu_*^4}{GM_* \dot{M}_D^2} \right)^{1/7},$$

where μ_* is the magnetic dipole moment of the central star and equals the product of the equatorial field strength B_* on the star times the cube of it radius R_*: $\mu_* = B_* R_*^3$. The quantity Φ_{dx} in our theory is the dimensionless magnetic flux of the stellar dipole (a pure number of order unity) that would have threaded the equator beyond R_x if this region had not been occupied by a disk whose surface layers, at least, are highly electrically conducting. In steady state, the spin rate of the star is regulated to the value appropriate for Keplerian rotation at R_x:

$$\Omega_* = \left(\frac{GM_*}{R_x^3} \right)^{1/2}.$$

Mass conservation in steady state requires that the disk accretion rate $\dot{M}_D$ divides into complementary fractions of X-wind outflow and funnel inflow onto the star:

$$\dot{M}_w = f\dot{M}_D, \qquad \dot{M}_* = (1-f)\dot{M}_D.$$

Angular momentum conservation in steady state requires

$$f = \frac{1 - \tau - \bar{J}_*}{\bar{J}_w - \bar{J}_*},$$

where τ is the dimensionless viscous torque just exterior to R_x and $\bar{J}$ is the dimensionless specific angular momentum averaged over mass-carrying streamlines (the wind in the case of $\bar{J}_w$, and the funnel flow in the case of $\bar{J}_*$). These quantities are the sum of two contributions, one carried in the gas, the other carried in the field (as a Maxwell torque); thus,

$$\bar{J}_w = \bar{J}_w^{\rm g} + \bar{J}_w^{B}; \qquad \bar{J}_* = \bar{J}_*^{\rm g} + \bar{J}_*^{B}.$$

Energy flow within the system proceeds as follows. The rate of energy radiated in steady state by a viscous accretion disk that has an inner radius R_x is given by standard theory as

$$L_D^{\rm acc} = \left(\tau + \frac{1}{2}\right)\frac{GM_*\dot{M}_D}{R_x}.$$

The mechanical luminosity carried by the gas in the wind equals

$$L_w^{\rm g} = f\left(\bar{J}_w^{\rm g} - \frac{3}{2}\right)\frac{GM_*\dot{M}_D}{R_x}.$$

The Poynting luminosity carried by the electromagnetic field of the wind equals

$$L_w^{B} = f\bar{J}_w^{B}\frac{GM_*\dot{M}_D}{R_x}.$$

The mechanical luminosity (kinetic plus gravitational potential energy) carried by the gas in the funnel flow equals

$$L_{\rm fun}^{\rm g} = (1-f)\left(\bar{J}_*^{\rm g} - \frac{3}{2}\right)\frac{GM_*\dot{M}_D}{R_x}.$$

The Poynting luminosity carried in the electromagnetic fields of the funnel flow equals

$$L_{\rm fun}^{B} = (1-f)\bar{J}_*^{B}\frac{GM_*\dot{M}_D}{R_x}.$$

The last two are negative, implying that the mechanical and field energy flows are directed oppositely to the funnel matter flow into the X-region. In contrast, viscous accretion can require up to three times more energy (if $1 > \tau > 0$) than released in orbital energy ($GM_*\dot{M}_D/2R_x$), and driving a wind also requires positive energy input: $L_w^{\rm g} + L_w^{B} = (\bar{J}_w - 3/2)GM_*\dot{M}_w/R_x$ with $\bar{J}_w > 3/2$ if the wind has finite terminal velocity at infinity. A little algebra recovers the identity that the funnel flow luminosities into the X-region exactly make up for the extra amount required by the existence of the viscous torque τ and the launching of the X-wind,

$$L_D^{\rm acc} + L_w^{\rm g} + L_w^{B} + L_{\rm fun}^{\rm g} + L_{\rm fun}^{B} = 0,$$

if f is given by the value required by angular momentum balance: $f = (1 - \tau - \bar{J}_*)/(\bar{J}_w - \bar{J}_*)$. Angular momentum conservation in this problem implies energy conservation, because the only way here to transfer energy (in the inertial frame) is to exert torque.

The only energy reservoir in the system is the release of gravitational potential energy when matter drops from a very large radius by first spiraling slowly through the disk under the (assumed) action of viscous torques, and then separating it into two parts when it encounters the magnetosphere of the central star: one fraction f blown out as an X-wind, the other fraction $1-f$ accreting onto the star by magnetized funnel flow. Upon impact with the star, the dissipation of the funnel-flow's kinetic energy in the frame that corotates with the star creates a radiative luminosity in hot spots equal to

$$L_{\rm hot} = (1-f)\frac{GM_*\dot{M}_D}{R_*}\left(1 + \frac{R_*^3\sin^2\theta_{\rm h}}{2R_x^3} - \frac{3R_*}{2R_x}\right),$$

where θ_h is the mean colatitude (measured relative to the pole) of the impact sites. Notice that the accretion luminosity of the star L_{hot} approaches the naive expression $GM_*\dot{M}_*/R_*$ if $R_* \ll R_{ast}$, but L_{hot} can be much smaller than the accretion luminosity of the disk L_D^{acc} if $R_* \approx R_x$ (as may apply to a rapidly accreting protostar) and θ_h moves to the equatorial plane $\theta_h = \pi/2$. In all cases, L_{hot} is less than naive expectations.

The excess gravitational energy not released as radiation in the disk or the hot spots is transported magnetically to drive the outflow. Thus, both viscous and magnetic torques have the property that they transfer angular momentum and energy from the angular-momentum-poor but energy-rich inner portions of the system to the angular-momentum-rich but energy-poor outer portions of the system.

From the detailed calculations (see Ostriker & Shu), we obtain the following "preferred" values for the crucial dimensionless numbers:

$$\tau \approx 0; \qquad \bar{J}_* \approx 0; \qquad \bar{J}_w \approx 3, \qquad \Phi_{dx}^{-4/7} \approx 0.9.$$

We are fairly confident about the theoretical arguments that produce the final three numbers, but the estimate $\tau \approx 0$ represents only a lower limit. This lower limit, combined with the other values, yields $f \approx 1/3$.

For the "preferred" model, when we are given M_*, B_*, R_*, $\dot{M}_D$ (and the assumption $\tau = 0$), everything else in bulk is predicted, although the degree of collimation of the wind remains to be calculated. The predicted quantities include the rotation rate of the central star, the size of the inner disk hole, the size of the largest magnetic loops, the terminal velocity of the X-wind, the impact velocity and luminosity of the funnel flow at the stellar surface, the size and location of the hot spots, and the fractions f and $1 - f$. The model is highly susceptible therefore to observational confirmation, refinement, or disproof.

6. FUTURE DIRECTIONS

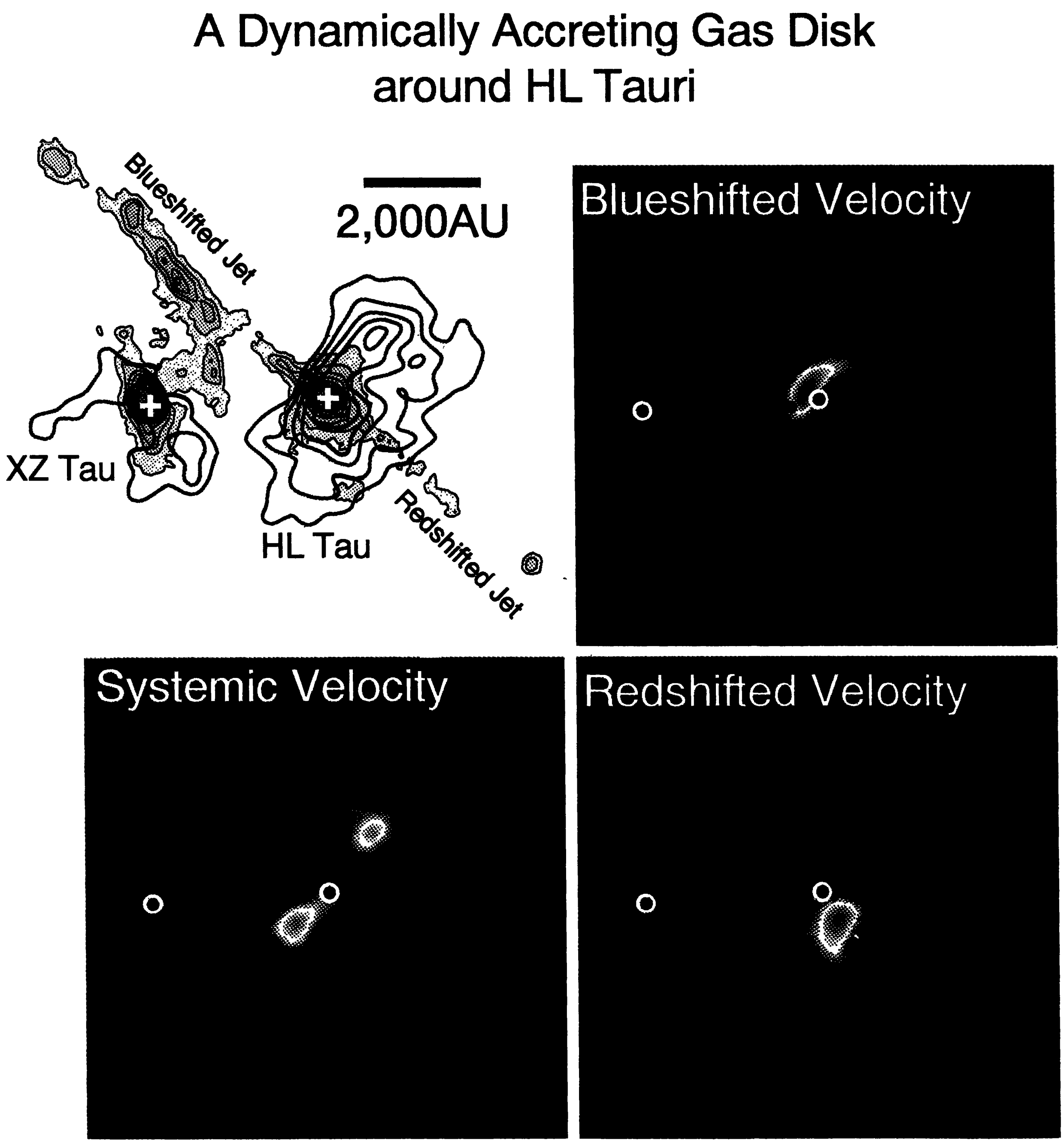
Does the generalized X-wind/funnel flow model represent the final unification scheme? No. If one examines the history of this kind of thing, one finds that "unification schemes" never explain everything. There are always phenomena that lie outside the teachings of the church. The present case is no exception. A cloud already exists on the horizon. We have taken the point of view that spheres, disks, and outflows owe their existence to the spin angular momentum problem. But in addition to spin, many astrophysical objects also possess orbital motions. An understanding of binary star systems must deal with the origin and resolution of this additional problem. Indeed, an entirely different kind of unification scheme – originated by Hoyle, and continued in the present day by Bodenheimer, Boss, and many others – adopts the basic viewpoint that *hierarchical fragmentation* presents the key to understanding binaries, multiple star systems, and clusters. Since intermediate-mass and high-mass stars tend to be born in tight groups (see the reviews of Evans and Walmsley), this different approach may offer insights into the formation of these kinds of stars. The problem is similar to that of large-scale structure in cosmology.

Cosmologists interested in large-scale structure have the advantage over us in that their basic physics is simpler (no magnetic fields and no turbulence), and their initial conditions (small-amplitude fluctuations in a Friedmann universe) are better defined. We have the advantage over them in that we understand the structure, history, and evolution of our final objects (stars) better than they understand the properties of their final objects (galaxies). Moreover, we can observationally study many examples of our initial states (giant molecular clouds), while cosmologists must measure with great difficulty tiny fluctuations in the (one and only) cosmic microwave background. Finally, we do not need to speculate about the nature of a dark matter component, nor worry about whether a certain number is 50 or 80.

Like the problem of large-scale structure, the program of hierarchical fragmentation is notoriously difficult and complex, and much remains to be done both observationally and theoretically. If a unification scheme does emerge from the effort to understand the origin of multiple stars and orbital motions, it will be interesting to see how it incorporates the feedback from the winds and other phenomena that arise, we assert, because of the spin angular momentum problem of individual stars.

In the interim we should not underestimate the rosy future that lies ahead for the known but incompletely understood aspects of our subject. Ours is a field abundantly rich in physical phenomenology. For example, T Tauri stars and their embedded cousins alone contain as many topics for study as the entire field of active galactic nuclei – infrared and ultraviolet excesses, narrow and broad forbidden lines, narrow and broad permitted lines, continuum radiation from radio waves to x-rays, reprocessing in dusty envelopes, polarization from scattered radiation through holes in those envelopes, accretion disks, energetic flares observable at radio to x-ray wavelengths, extended outbursts associated with thermal instabilities in time-dependent disks, magnetospheric interactions between the central objects and the surrounding disks, spiral and bar instabilities in self-gravitating disks, radio and optical jets, radio lobes swept up or entrained by outflows, shocked knots that have measurable proper motions, etc. Observationally, we have the further good fortune of having objects near enough to map by interferomeric techniques and bright enough for high-resolution spectroscopy. And theoretically, we know, in principle, all the basic physics possible for the central object (a pre-main-sequence star rather than a rotating black hole), as well as where it has been (a molecular cloud core), and where it is going (a main-sequence star).

Finally, we have bright new vistas potentially opening up for us with the advent of the new generation of instruments described by Paul Ho. Foremost among the foreseeable discoveries will be the revitalized frontier of the formation of planetary systems. With resolved circumstellar disks, where we can study the internal structures, analyze the radial distribution of the temperatures, densities, kinematics, chemical compositions, gas and dust contents, we will no longer have to speculate solely on the basis of one example where the clues are 4.5 billion years old. The next few decades promise to be an exciting time for the study of star and planet formation. It is hard to predict where the most important progress will come in the new millennium, but I fully expect YLAs to continue to make many of the crucial discoveries that lie ahead.



Top Left:	Integrated intensity map of ^{13}CO (J=1–0) superimposed on the optical jet observed by Mundt et al. (1988)
Top Right:	^{13}CO map for blueshifted velocity
Bottom Left:	^{13}CO map for systemic velocity
Bottom Right:	^{13}CO map for redshifted velocity

Fig. 2.— (b) HL Tau (figure from Hayashi et al. 1993).

HO (see page 363)