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ANGULAR MOMENTUM AND PROTOSTELLAR DISKS

Richard B. Larson

Yale University Observatory

ABSTRACT. In a realistic collapsing cloud, deviations from perfect axial symmetry will produce gravitational torques that alter the distribution of angular momentum. If differential rotation leads to the development of trailing spiral features of large amplitude, angular momentum will be transferred outward on an orbital time scale. Any disk formed by the collapse of a rotating cloud will be a fragile structure, and almost certainly highly unstable to the growth of trailing spiral density perturbations of large amplitude. Thus it seems unavoidable that rapid outward transfer of angular momentum by gravitational torques will eventually occur in any realistic collapsing cloud. The only stable outcome of the collapse is a system in which most of the mass is in a central star or binary system, and less than half of the mass remains in a disk around the star.

If many newly formed stars are surrounded by residual disks whose mass is not much smaller than the maximum stable mass, accretion of material from such disks, possibly driven by gravitational torques induced by protoplanetary condensations, could have significant consequences for the observable properties of young stars. In particular, FU Orionis-type outbursts could be caused by sporadic runaway accretion of the inner part of a residual disk, occurring when frictional heating of the outer layers of the star causes it to expand rapidly. Mass ejection could also be powered by disk accretion if part of the kinetic energy released is converted into magnetic energy and causes strong flaring activity.

1. THE ANGULAR MOMENTUM PROBLEM AND GRAVITATIONAL TORQUES

If a star or stellar system is to form in a collapsing protostellar cloud that has even a small amount of rotation, most of the angular momentum of the cloud must somehow be lost or redistributed during the star formation process. During the early stages of the collapse, magnetic torques may play an important role in maintaining slow rotation in protostellar clouds (Mouschovias 1978), and this may account for the angular momenta of at least the wider binary systems. However, a magnetic field is expected to decouple from the gas long before stellar densities are reached, so some other mechanism must act to transfer angular momentum during the later stages. Turbulent viscosity could also transfer angular momentum outward, either during the initial collapse or subsequently in a disk formed as a result of the collapse, but this postulated mechanism is ad hoc, since no way is known to sustain the required strong turbulence throughout a protostellar cloud or disk.

In many collapsing protostellar clouds, most of the angular momentum may go into the orbital motion of a binary or multiple system of condensations; tidal torques could then play a role in removing residual spin angular momentum from the individual pre-stellar condensations (Larson 1977). More generally, it is possible that gravitational torques could play an important role in redistributing angular momentum in collapsing clouds whenever the mass distribution is non-axisymmetric. In general, non-radial gravitational forces will be present because a real collapsing cloud will not be precisely axisymmetric, but will be somewhat irregular. If the cloud has any tendency toward fragmentation, irregularities in its structure will even be amplified as it collapses, and such irregularities will generally tend to be wound up by differential rotation to produce trailing spiral structures. Such trailing spiral features were found in some of the simulations of 3-dimensional collapse by Larson (1978). Associated with any trailing spiral density enhancement is a gravitational torque that transfers angular momentum outward (Lynden-Bell and Kalnajs 1972); therefore, gravitational torques may be of general importance in transfering angular momentum outward in collapsing clouds and allowing them to become more centrally condensed.

Gravitational torques may be especially important if multiple condensations form and orbit around each other; these condensations will generate trailing spiral-shaped wakes that exert a gravitational drag on them, causing them to spiral rapidly closer together. This result has been found in some numerical simulations of fragmenting collapsing clouds (Larson 1978, Gingold and Monaghan 1981, Boss 1982). In all cases where trailing spiral density perturbations of large amplitude occur in numerical simulations of rotating systems, including simulations of galaxies, the time scale for outward transfer of angular momentum and the resulting central concentration of mass is of the same order as the orbital period.

Even if a cloud collapses with perfect axial symmetry and conservation of angular momentum to form a disk, such a disk will probably be subject to instabilities tending to destroy its axial symmetry and generate strong trailing spiral density perturbations; once again, rapid outward transfer of angular momentum will result. If it can be demonstrated that any disk formed by the collapse of a rotating cloud is unstable, then non-axisymmetric perturbations and gravitational redistribution of angular momentum must necessarily occur at some stage in the collapse. The role of instabilities and gravitational torques in protostellar disks will be discussed in detail elsewhere (Larson 1983); here we summarize some of the principal results.

2. STABILITY OF PROTOSTELLAR DISKS

Extensive recent work on the stability of disks, as summarized by Toomre (1981), has shown that much of the complicated behavior of unstable disks, even the large-scale or "global" responses, can be understood on the basis of the local stability analysis first carried out by Goldreich and Lynden-Bell (1965). An important prediction of this analysis is that the growth of density perturbations is enhanced by the shear present in a differentially rotating disk; as a result, shearing disturbances in a marginally stable disk can grow into trailing spiral patterns of large amplitude. This phenomenon has been called "swing amplification" by Toomre. Since the resulting spiral patterns are transient and the total growth in amplitude is finite, although it may be very large, it is necessary to estimate the amount of amplification that can occur as a function of the properties of the disk.

If the sound speed c and the epicyclic frequency κ in the disk are known, the maximum growth factor for shearing disturbances depends on the disk surface density μ and on the wavelength λ of the disturbances. If the wavelength is taken to be that for which the growth rate is largest, the amount of amplification attainable depends on the ratio μ/μ_c, where μ_c is a critical density given by

$$\mu_c = c\kappa/\pi G.$$

For an infinitely thin disk, instability to axisymmetric disturbances occurs for $\mu > \mu_c$, while for a self-gravitating isothermal disk of finite thickness, axisymmetric instability occurs for $\mu > 1.5\ \mu_c$. For shearing, swing-amplified disturbances in a disk of finite thickness, the maximum amplification factor is approximately 3 for $\mu/\mu_c = 0.9$, 15 for $\mu/\mu_c = 1.2$, and 100 for $\mu/\mu_c = 1.5$ (Larson 1983). Thus any disk with $\mu > \mu_c$ is susceptible to significant amplification of shearing disturbances. For $\mu > 1.5\ \mu_c$, the amplification factor becomes very large, and the disk also becomes unstable to axisymmetric modes.

During the early stages of collapse, a protostellar cloud is expected to remain approximately isothermal, and any disk that forms in it will also be nearly isothermal, as long as the density does not become too high. Analytical models of isothermal disks with surface density $\mu(r) \propto r^{-1}$ and rotational velocity $V(r)$ = const. have been found by Toomre (1982) and by Hayashi, Narita, and Miyama (1983). These isothermal disks have constant mass per unit specific angular momentum dM/dh, as does a rigidly rotating uniform cylinder, and they approximate the structure of the disks obtained in some calculations of the collapse of rotating clouds (Norman, Wilson, and Barton 1980; Hayashi et al. 1983).

For an isothermal disk, the stability parameter μ/μ_c is related analytically to the flattening parameter $n = V^2/2c^2$, and this in turn is related to the quantity (G/c)dM/dh, which by assumption is conserved during the collapse (Larson 1983). For any isothermal disk that is stable to radial collapse, $\mu/\mu_c > 0.83$, implying susceptibility to swing amplification of disturbances by at least a factor of ~ 2. For any isothermal disk formed by the collapse of a rotating cloud, the numerical criteria for collapse of Boss and Haber (1982) imply that (G/c)dM/dh must be greater than 3.5, and hence that μ/μ_c must be greater than 1.1; such a disk would be susceptible to swing amplification by at least a factor of ~ 8. Thus any isothermal disk formed by the collapse of a rotating cloud must be a fragile structure, in which density perturbations exceeding ~ 10 % in amplitude can lead to strong spiral distortions and hence significant restructuring of the disk by gravitational torques.

In fact, disks formed from real collapsing clouds are likely to be considerably more unstable than this limiting case. Observations of nearby protostellar clouds by Myers and Benson (1983) show generally very slow rotation, and they imply a median upper limit of 0.04 on the ratio β of rotational to gravitational energy. This implies a median lower limit on (G/c)dM/dh of 6.8, and a median lower limit on μ/μ_c in any resulting disk of 2.4. Such a disk would be highly unstable and would rapidly develop strong spiral distortions that would transfer angular momentum outward, even before all of the protostellar mass has collapsed into the disk. Thus it seems inescapable that at some stage during the collapse of a protostellar cloud with realistic initial conditions, large deviations from axial symmetry and rapid outward transfer of angular momentum by gravitational torques will occur.

The above conclusion is based on the assumption that the collapsing cloud and any disk that forms in it remain isothermal at all times, but this assumption will cease to be valid if the disk becomes very compact and its surface density very high. An opposite case was considered by Cameron and Pine (1973), who constructed models of disks that were assumed to be adiabatic rather than isothermal. These disks are marginally stable and have $\mu \sim \mu_c$, but they have a very short time scale for radiative cooling, so that cooling will soon reduce μ_c and make these disks unstable. Thus it does not seem possible to avoid the occurrence of non-axisymmetric distortions and gravitational torques, even in the non-isothermal regime. The only stable outcome of the collapse will then be a system in which most of the mass is in a central star or binary system, and the amount of mass remaining in any circumstellar disk is small enough that the disk is stable.

3. REMNANT CIRCUMSTELLAR DISKS

The maximum mass that can be present in a stable disk around a newly formed star depends on the critical density $\mu_c = c\kappa/\pi G$ and hence on the sound speed c and the epicyclic frequency κ as functions of distance from the star. To consider a specific example, we assume that the central star has the properties of the present Sun, and that the temperature in the disk is given by $T = 300\ r(\mathrm{AU})^{-1/2}$ K. We also assume, as will be approximately justified, that most of the mass is in the central star, so that the rotation law in the disk is Keplerian. Finally, we suppose, somewhat arbitrarily, that adequate stability against the growth of non-axisymmetric perturbations is ensured if $\mu < 0.5\ \mu_c$. The maximum stable disk mass interior to radius r is then

$$M_d(r) \ < \ 0.14\ r(AU)^{1/4}\ M_\odot .$$

Since the epicyclic frequency varies with stellar mass as $M^{1/2}$ and the sound speed varies with luminosity as $L^{1/8}$, the maximum stable disk mass varies as the product of these two factors, and is therefore nearly proportional to the stellar mass.

A stable remnant disk with the size of our solar system (r = 40 AU) can accordingly have a mass no larger than about 1/3 of the mass of the central star; this is in approximate agreement with the numerical results of Cassen et al (1981). The maximum possible radius and mass of a remnant disk depend on the total angular momentum of the system; for example, if we adopt an upper limit of $\beta < 0.04$ for the amount of rotational energy in a typical protostellar cloud, the maximum disk radius is $\sim$ 2500 AU, and the corresponding maximum disk mass is about 1.0 times the mass of the central star. Thus, in most collapsing protostellar clouds, most of the material that is not dispersed must go into a central star or binary system, and less than half can remain behind in a disk. In other words, the efficiency of star formation in individual collapsing protostellar clouds is predicted to be high, of the order of 50 % or more, apart from any material that may be dispersed by effects such as stellar winds. This prediction is consistent with observations of regions such as the Taurus clouds, where typical protostellar cloud cores have masses of $\sim 2\ M_\odot$ (Myers and Benson 1983) and are associated with T Tauri stars having masses of the order of $\sim 1\ M_\odot$. (Cohen and Kuhi 1979).

Whether stars actually form with circumstellar disks that approach the maximum stable mass cannot be predicted without a detailed knowledge of the formation process. Some numerical simulations (e.g. Larson 1978) suggest the formation of substantial disks; also, if the mechanism for transfer of angular momentum in protostars involves gravitational torques in circumstellar disks, a substantial amount of mass would have to be present at some stage in such a disk to transfer the angular momentum. However, it is possible that the star formation process does not proceed via the formation of a disk but involves, perhaps, violent interactions and mergers between several dense clumps that fall together, as well as the ejection of some material from the system. In this case relatively little material might remain in a disk.

The only remnant disk for which we have any detailed information is our planetary system, and the initial mass usually inferred from its present contents and assumed in models of the early solar nebula is about ten times smaller than the maximum stable mass (e.g. Hayashi 1981). If the solar nebula had much more mass than this, it would be difficult to understand why more of it did not condense into planets, and to account for the removal of the excess mass; thus it seems unlikely that the solar nebula had a mass approaching the maximum stable mass. However, it still seems possible that some stars could at an early stage possess circumstellar disks of substantial mass, perhaps as much as a few tenths of a solar mass.

There is some tentative evidence for disks around many young stars, although little or no quantitative information is yet available. For example, Hyland et al. (1979) suggest that a possible interpretation of their infrared observations of η Car is that this star is surrounded by a non-uniform disk of dust with a radius of ∿ 3000 AU. The polarization data of Warren-Smith et al. (1979) are also consistent with the presence of a disk around η Car. Smith et al. (1982) suggest that the infrared radiation from around FU Ori originates in an extended disk, and some possible evidence for a disk around the similar object V1057 has been noted by Herbig (1977). Canto et al. (1981) and Gething et al. (1982) have presented evidence for a disk associated with R Mon. In the spectra of many rapidly rotating pre-main-sequence stars, Smith, Beckers, and Barden (1983) have found narrow absorption lines which they attribute to circumstellar disks close to these stars. Radio mapping of molecular clouds has also shown evidence for larger-scale disks associated with luminous young stars (e.g. Bally and Scoville 1982, Bally 1982). All this evidence suggests that disks of some sort may be quite common around young stars, although it does not yet significantly constrain models of such disks.

4. ACCRETION FROM DISKS

If many young stars are surrounded by remnant protostellar disks, interactions between these disks and their central stars may have significant consequences for the observable properties of young stars. Here we consider some possible effects of continuing accretion of material from a disk onto the central star. Models of protostellar accretion disks in which the inflow is driven by turbulent viscosity have been considered by a number of authors, including Lynden-Bell and Pringle (1974), Cameron (1978), and Lin and Papaloizou (1980). The turbulent viscosity assumed in these models is ad hoc, but it is possible that gravitational torques due to density fluctuations in the disk play a similar role, especially if the mass of the disk approaches (or exceeds) the maximum stable mass. Even if the disk is stable, any disturbances that occur and generate small density fluctuations can cause significant gravitational transfer of angular momentum over many orbital periods; this effect can be important if the amplitude of such density fluctuations is greater than about 10^{-2} (Larson 1983).

Even if no external perturbations generate density fluctuations, the material in the disk will eventually begin to collect into planetary or pre-planetary condensations, and these will induce trailing spiral density enhancements and hence gravitational torques that transfer angular momentum outward (Julian & Toomre 1966). If a planet or protoplanet of mass M_p forms in a disk around a star of mass M, the time scale for induced transfer of angular momentum in the disk is of the order of $(M/M_p)^2$ times the orbital period of the planet, and is considerably shorter than this in the immediate vicinity of the planet. Thus, if a planet with the mass of Jupiter (10^{-3} $M_\odot$) is present, significant restructuring of the disk can occur in a time of the order of 10^6 years or less (Larson 1983, Goldreich and Tremaine 1980).

The time required for the formation of planets is very uncertain, but has been estimated to be of the order of 10^6 years for the Earth and 10^7 years for Jupiter, assuming a solar nebula with a mass of a few percent of the Sun's mass (Hayashi 1981). In a more massive disk, the time scale for planetary accumulation would be shorter and the planets formed would be more massive than those in our solar system. If objects more massive than Jupiter form, they would cause rapid dynamical evolution of the disk. The resulting structure of the system could become extremely complex (as is suggested by the example of Saturn's rings), and its evolution cannot be predicted in detail, but one outcome would almost certainly be that the innermost part of the disk, including any planets or forming planets, would lose angular momentum to the outer part and be accreted by the central star.

Such accretion could have significant observable consequences. For example, if a mass of 0.1 $M_\odot$ were accreted over a period of 10^6 years by a star with a mass of 1 $M_\odot$ and a radius of 2 $R_\odot$, the gravitational energy released would be enough to provide an average luminosity of about 1 $L_\odot$, comparable to the luminosities of many T Tauri stars. Probably the disk will be non-uniform in structure and the accretion process will be variable in time; sporadic enhancements in the accretion rate could then have marked effects on the observable properties of the star. It is even possible that planets or protoplanets could be accreted by the star, with spectacular effects; indeed, the infall of Jupiter-sized objects was one of the possibilities listed by Herbig (1977) as an explanation of the FU Orionis phenomenon.

An important difference between disk accretion and the spherically symmetric accretion that occurs in spherical protostar models is that, in the disk case, the incoming material is optically thick. In most of the spherical protostar calculations, the freely infalling material just outside the shock front at the surface of the star has very low density and optical depth, so that the energy released in the accretion shock is immediately radiated away and contributes to the luminosity of the protostar. In contrast, in an accretion disk the radial inflow velocity is small, and the density and optical depth of the disk are high. Moreover, because of its high density, the accreted disk material will spiral into the deeper, optically thick layers of the stellar envelope before most of its kinetic energy is dissipated. Therefore this energy will not be radiated away immediately as in the spherical case, but will be deposited as heat in an optically thick outer zone of the star. If energy is deposited in an optically thick outer region faster than it can be radiated away at the surface of the star, this will cause expansion of the envelope and hence an increase in the radius and luminosity of the star. This is qualitatively what is required to account for the FU Orionis phenomenon (Larson 1980).

We remark that in the calculations of protostellar collapse by Narita, Nakano, and Hayashi (1970), which started from initial densities many orders of magnitude higher than those of Larson (1969), the infalling material outside the accretion shock is optically thick, so that the energy released is not immediately radiated but is stored as heat in the outer layers of the star, causing it to have a much larger radius and luminosity than in the models of Larson (1969).

5. THE FU ORIONIS PHENOMENON

Can accretion of material from a remnant protostellar disk account for the FU Ori phenomenon? Without knowing more about the structure and evolution of the disk it is not possible to predict any details, but it does not seem too difficult to account for the orders of magnitude involved. The energy associated with the flare-up of V1057 Cyg was about 10^{45} ergs, while for FU Ori the energy was probably about 10^{46} ergs (Larson 1980). Herbig (1977) has estimated that the FU Ori phenomenon recurs in typical T Tauri stars with a period of the order of 10^4 years; thus as many as $\sim$ 100 such outbursts might occur over a period of 10^6 years, the age of a typical T Tauri star. The total energy required is then of the order of $\sim 10^{47} - 10^{48}$ ergs. This amount of energy would be made available if a star with a mass of 1 $M_\odot$ and a radius of 2 $R_\odot$ were to accrete a total of $\sim$ 0.1 - 1.0 $M_\odot$ from a circumstellar disk; this is consistent with the maximum amount of mass that could be present in a remnant protostellar disk. The period of $\sim 10^6$ years for the accretion process inferred from the ages of T Tauri stars may also be consistent with the predicted time scale for dynamical evolution of the disk if this evolution is driven by planetary torques and if the relevant time scale is that of planetary accumulation processes, as discussed above.

It is also plausible that the accretion process would occur in a series of discrete events rather than continuously, for a number of possible reasons: (1) the disk may be very non-uniform in structure; (2) if the disk is marginally stable, instabilities could trigger episodes of rapid accretion; (3) heating and expansion of the outer layers of the star can occur as a runaway process, since mass and energy will continue to be added to these layers as the star expands and swallows up more and more disk material. This runaway expansion can lead to the accretion of a significant amount of mass in a short time. For example, the observations of V1057 Cyg show that during its flare-up this star expanded by about a factor of 4 in radius from 4 $R_\odot$ to 16 $R_\odot$ (Herbig 1977); the star would thereby absorb about 2×10^{-2} $M_\odot$ from the inner part of a marginally stable disk, or 3×10^{-4} $M_\odot$ from a solar nebula of minimum mass (Hayashi 1981). For comparison, the mass needed to power the outburst of V1057 Cyg is about 2×10^{-3} $M_\odot$, and this could be provided by a disk of intermediate mass.

Simple models of stars with heated outer envelopes have been constructed by Larson (1980), and they show that the radius attained depends mainly on the energy per unit mass $\Delta E/\Delta M$ added to the envelope. If this quantity is equal to 0.5 times the gravitational energy per unit mass at the initial radius of the star, which is the most that could be obtained by converting rotational kinetic energy into heat at this radius, the final radius is predicted to be about 25 $R_\odot$ for an initial radius of 4 $R_\odot$. The fact that the actual maximum radius attained by V1057 Cyg was somewhat smaller than this is not surprising because (1) less than 100 % of the rotational energy of the disk is available to be converted into heat, since the star has a finite rotational velocity, and (2) some of this energy may be converted into other forms, such as magnetohydrodynamic energy.

It was suggested by Larson (1980) that the FU Ori phenomenon is due to a rotational instability in a rapidly rotating star. However, the fact that most T Tauri stars rotate slowly (Vogel and Kuhi 1981) makes this mechanism seem less plausible; also, both FU Ori and V1057 Cyg are rotating more rapidly than most T Tauri stars, which is the reverse of what would be expected on this basis, since the expansion in radius of these stars should have slowed down their rotation. On the other hand, the disk accretion mechanism suggested here would spin up the outer layers of a star during the flare-up, and this would be consistent with the higher than average rotational velocities of FU Ori and V1057 Cyg. The result of Smith et al (1983) that the presence of disks around young stars is strongly correlated with rapid rotation is also consistent with the possibility that young stars generally rotate slowly but may be spun up by accretion from disks. We recall that there is in fact some evidence for circumstellar disks around both FU Ori and V1057 Cyg, as noted above.

Thus the present (still fragmentary) evidence seems consistent with a disk accretion mechanism for the FU Ori phenomenon. Another attractive feature of an accretion theory is that it would be easy to explain the stars discussed by Herbig (1977) as possible less spectacular analogues of FU Ori by simply scaling down the amount of accretion involved. In fact, considerable variations from case to case might be expected, depending on the amount of material remaining in a circumstellar disk and on the details of its structure. One can imagine many possibilities for the form of the accreted matter, including smoothly distributed gas, rings of gas and/or solid materials, swarms of small planetary or cometary objects, and even major planets.

6. OTHER IMPLICATIONS

The energy released by the accretion of disk material at the surface of a young star may also have other important effects. There is much evidence for vigorous solar-type magnetohydrodynamic activity on the surfaces of T Tauri stars, and it seems possible that such activity would be greatly enhanced in the region where incoming disk material interacts with the outer layers of the star and high velocity motions are present. Some fraction of the kinetic energy released in this region might go into magnetic energy, producing strong flaring activity and a strong stellar wind. Such activity might be particularly violent during periods of rapid accretion; in fact, there is evidence that both FU Ori and V1057 Cyg ejected shells of material at the time of their outbursts (Herbig 1977).

Much evidence also indicates the presence of strong bipolar outflows from newly formed stars. Collimation by an accretion disk has often been suggested as an explanation for the bipolar nature of these flows. However, if a wind is generated at or near the surface of a disk, it will tend to flow in two opposite directions from the outset, without the need for any special collimation mechanism (Torbett 1982). If the energy source for the wind is accretion, both inflow and outflow could be occurring simultaneously but in different directions, and this could provide the long-sought reconciliation between theoretical expectations that a forming star should continue for a time to gain mass by accretion, and the observational evidence indicating that strong outflows occur as soon as any kind of stellar object is present. The absence of unambiguous evidence for accretion may simply be a result of the fact that the accretion flow is optically thick and therefore not directly observable. The best evidence for accretion and for the final stages of stellar formation may then in fact be provided by the violent activity, mass ejection, and FU Ori-type flare-ups that are characteristic of the earliest stages of stellar evolution.

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DISCUSSION

Basri: Do you feel that the disks you have suggested should be commonly found around T Tauri stars, or are they only associated with the less common outburst stars?

Larson: If the scenario I described is generally correct and stars form as a result of outward transfer of angular momentum in disks, I would expect disks to exist around most T Tauri stars, at least at a sufficiently early stage. However, this scenario is only a limiting case, and star formation could in general be a much more chaotic process, in which case it would be difficult to make any predictions about the occurrence or properties of disks. I think that it has to be treated as an observational problem, about which it is beyond the power of current theory to make predictions.

Basri: What effect would the canonical mass loss of 10^{-7} - 10^{-8} $M_{\odot}$/yr have on sweeping these disks away?

Larson: If a disk has as much mass as, say, 0.1 $M_{\odot}$, and if this matter is in a thin flat layer, I would not expect a T Tauri wind to have much effect on the disk. A wind generated at the surface of a disk would not, of course, act directly to sweep away the disk.

Rydgren: What does this scenario predict with regard to the rotational velocities of the formed stars? Do we still need additional angular momentum loss?

Larson: Yes, probably. I would still expect newly-formed stars to be rotating rapidly at some sufficiently early stage. The low rotational velocities of most T Tauri stars would then require an additional braking mechanism, such as a conventional stellar wind.

Ambartsumian: (*Comment*) The new discoveries about the processes going on in regions of recent star formation (the outflow of matter, the expansion of the system of H_2O masers, etc.) have made necessary to suppose that the contraction assumed by the followers of the theory of gravitational condensation is finishing before we can observe the newly formed stars. Now I have understood that we must suppose also that the star must get rid of the rotational momentum before we can see it. Is it not too much?

Garay: (*Comment on Dr. Ambartsumian remarks*) Drs. Reid, Moran and myself studied the dynamical relationship between compact H II regions and the associated OH maser phenomena in ten star-forming regions and found that the OH masers are part of a remnant envelope collapsing towards the newly-formed star. Thus we are *seeing* a collapsing stage in the formation of very massive stars.

Feigelson: (*Comment*) Regarding the possible relation between flaring and proto-planetary disks in T Tauri stars. Rydgren and colleagues have shown that the X-ray discovered pre-main sequence stars do not have dense dust shells. On the other hand, there are a number of properties of ancient meteorites and lunar material that may reflect the effects of enhanced flaring in the early Sun (Feigelson, *Icarus*, 51, 155). Also, X-rays were not seen in V1057 Cyg, although the upper limit is not very strong.

Königl: 1) How is the small internal scale of the disk discussed in your model related to the observed interstellar disks of scales 10^{15} - 10^{16} cm? 2) In reference to a recent proposal by F. Shu, that the mass scales of stars are determined by the onset of deuterium burning and the initiation of convective instability, what is the mechanism in your picture which determines the star's final mass?

Larson: 1) The only very definite statement that I could make is that if a protostellar cloud with a radius of $\sim$ 0.1 pc and $\beta < 0.04$ collapses to a disk, the disk would have a radius less than $\sim$ 2500 AU ($4{\times}10^{16}$ cm). The outer part of such a disk might be identifiable with some observed "interstellar disks". It is also possible that infall of material from a larger region could form a larger disk. Probably the outer part of any disk would be thicker and less regular than the inner part. 2) In my simple-minded picture the collapsing protostellar cloud has a well-defined and finite total size and mass, and the mass of a star is determined when most of this protostellar mass has gone into the star. Of course, a real cloud probably does not have a well-defined boundary or total mass, but the total mass that can be assigned to the small protostellar clumps in regions like the Taurus clouds is nevertheless finite and not large.

Richard B. Larson: Yale Astronomy Department, Box 6666, New Haven, CT 06511, USA