N92-12847

The Evolution of Young Stellar Object Disks and Their Environment

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Progress and Accomplishments

Our main efforts have been directed toward determining the frequency of disk occurrence and the timescales for disk evolution for solar-type and intermediate mass stars. Results to date indicate that:

- Optically thick disks ($\tau > 1$ in regions sampled by excess emission $\lambda \leq 10\mu m$) are found around 30% to 50% of young ($\tau < 3$ Myr) stars of all masses $M < 3\ M_\odot$. Optically thick disks are found around PMS stars of higher mass, but with unknown frequency. For the relatively limited sample of objects for which sub-mm and mm-continuum measurements are available, nearly all stars with $\tau > 1$ show disk masses $M_d > 0.01\ M_\odot$ ($\equiv M_{mm}$). Disk sizes range from ~10 AU to ~1000 AU. Hence *disks of solar system sizes, and of masses comparable to or greater than the minimum mass solar nebula appear to form around a large fraction of stars with* $M < 3\ M_\odot$.

- Nearly all optically thick disks show evidence of (1) boundary layer emission diagnosed by "spectral veiling" at all optical wavelengths, and indicative of accretion of material onto the stellar surface; and (2) strong, broad Hα emission and forbidden line emission arising in energetic winds whose mechanical luminosity is proportional to the disk accretion luminosity. We conclude that *optically thick disks are accretion disks* with typical accretion rates $M_{acc} > 10^{-8}\ M_\odot/yr$.

- Disks survive as massive, optically thick structures extending nearly to the stellar surface for times ranging from t << 3 Myr to t~10 Myr around solar-type PMS stars. No optically thick disks have been identified around solar-type stars with ages t ≥ 30 Myr. The survival time for disks around more massive stars are not well established, particularly for stars $M > 3M_\odot$. However, the limited data available suggests that the disk survival times for such massive stars may be considerably shorter (t < 1 Myr) than those for solar-type stars.

- The descendants of massive, optically thick disks are disks containing masses of distributed micron-size dust grains $M < 10^{-4}\ M_\odot$; such disks are optically thin, and perhaps analogous to the structures observed to surround the intermediate mass stars Vega and β Pic.

Evidence of infrared excess emission consistent with emission arising in optically thin disks is found for stars of all masses. Stars surrounded by optically thin disks show none of the signatures associated with disk accretion (strong boundary layer emission; emission from spectral features arising in energetic winds). Hence, when disks become optically thin, disk accretion ceases.

- The presence of micron-size grains in optically thin circumstellar disks at distances r < 1 AU from the surface of solar-type stars, requires that such grains be continuously supplied to these disk regions; Poynting-Robertson or aerodynamic drag would otherwise deplete the grains on timescales short compared to the age of stars surrounded by optically thin disks. Small grains can be supplied either by collisions among larger grains or planetesimals; by evaporation of cometesimals gravitationally scattered into the inner disk regions; or by grains spiraling in from cold, outer disk regions (r >> 1 AU). Millimeter continuum observations currently underway can place stringent limits on the amount of distributed cold dust.

- Disks with apparent "inner holes" have been discovered. These are most likely structures in transition between disks that extend inward to the stellar surface and are optically thick throughout, and those that are optically thin. The presence of an "inner hole" may require that the inner regions of a disk be isolated from the exterior, optically thick disk regions. If so, the formation of a giant planet provides an attractive mechanism for tidally isolating the outer and inner disk regions. In this picture, the formation of a giant planet creates a gap in the disk. Gas and small grains located inward of the gap accrete onto the parent star; small grains, and possibly gas exterior to the gap survive for times t > 0.1 Myr.

- Our assessment of disk properties to date rests entirely on observations of emission arising from *dust* contained within the disk. Interferometric observations reveal CO mm-line emission arising in disk gas surrounding two extremely young solar-type PMS stars (HL Tau and L1551, IRS 5). The estimated gas mass for these systems lies in the range 0.1 to $1M_{\odot}$ (consistent with the masses determined from mm-continuum emission, "standard" dust emissivities, and an interstellar gas/dust ratio). Systematic searches for disk gas associated with stars of differing ages and masses are critical to determining characteristic times for the evolution of the gas component. However, no such searches are yet available, primarily because the sensitivity required demands extensive time on large mm-wave telescopes. We have searched for CO emission associated with G and K main sequence stars in the nearby Ursa Major cluster (d=25 pc; t~200-300 Myr). We find no evidence of CO emission associated with these stars, despite the fact that our measurements are sensitive enough to permit detection of $M \sim 10^{-4}\ M_{\odot}$ of gaseous material with a CO/H_2 ratio comparable to interstellar values. If CO survives in the circumstellar environment, then these observations suggest a gas survival time t < 200-300 Myr.

Projected Accomplishments

We plan to complete program of precise near- and mid-infrared measurements aimed at probing the distribution of dust located within the inner regions (r < 1 AU) of circumstellar disks surrounding solar-type stars. Our goal is to establish the magnitude of excess (above photospheric levels) near-infrared emission for a large (150) sample of stars with ages ranging from 30 Myr to 300 Myr, and to determine thereby the timescale(s) over which dust emission arising from inner disk regions becomes undetectable. Because dust in the inner regions of optically thin disks must be replenished continuously, we believe that this program will provide a strong astronomical constraint on the timescale(s) for assembling earth-mass bodies from planetesimals by monitoring the rate at which small grains are produced via collisions between planetesimals as a function of stellar age.

We also plan to carry out a program of sensitive mm-continuum observations aimed at:

- *Determining for solar-type stars with ages $t > 10$ Myr, the fraction, as a function of parent star age, that are still surrounded by circumstellar disks containing a significant ($M > 0.001\ M_{\odot}$) amount of material in the Giant Planet Region ($3 < r < 30$ AU).* These observations will provide an important astronomical constraint on the timescale available for building giant planets, and will *complement* recent infrared and mm-continuum surveys of much *younger* ($t \ll 10$ Myr) solar-type stars.

- Identifying solar-type stars in which planet-building may already have taken place at $r < 1$ AU. Such stars should be surrounded by disks which produce strong mm-continuum excess, but no near- and mid-IR excesses. This spectral signature is indicative of a star surrounded by a significant mass of cold dust located at distances of $r \gg 1$ AU, but little or no warm, micron-size dust located within ~1AU of the stellar surface. The development of such "inner holes" may signify that agglomeration of dust into planetesimals has begun in the terrestrial planet region.

Finally, we will pursue efforts to detect CO emission from disks surrounding young ($t < 100$ Myr) solar-type stars using the IRAM antenna.

Publications

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