Part 9

The Influence of Planets During Star Formation

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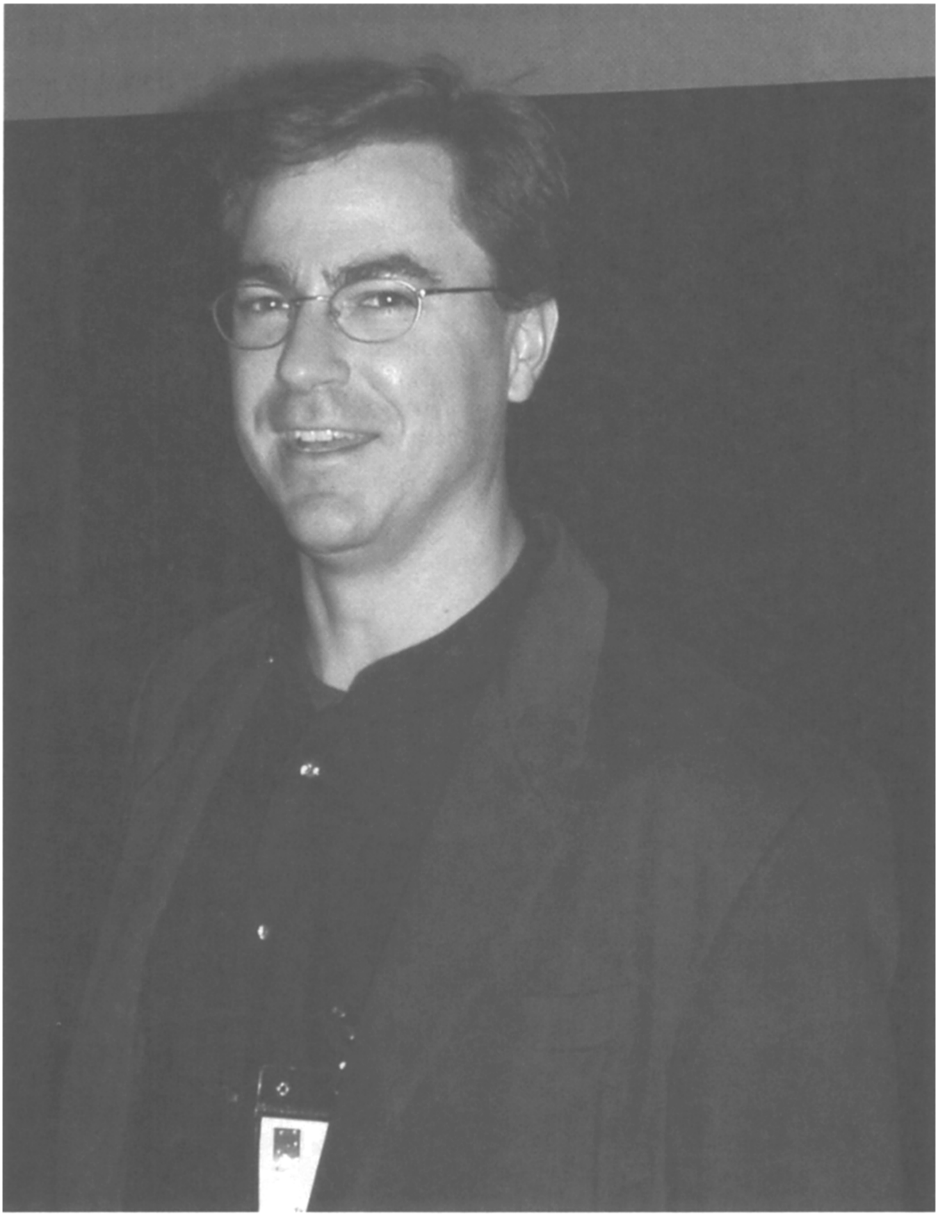

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Optical/IR Interferometry: Star Formation at sub-AU Scales

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Abstract. Intermediate to late stages of star formation are characterized by rising infrared and visible luminosities, with much of the most interesting physics concentrated in the inner regions within the immediate vicinity of the central protostar(s). Long-baseline optical and infrared interferometry is ideally suited to study of such bright, compact structures. Contributions from presently operational arrays, which are capable of resolving the brightest few dozen, will be reviewed. These results presage the potential for further dramatic advances in our understanding of star formation with observations from more advanced instruments now being built.

1. Introduction

The study of star formation has undergone revolutionary change in recent decades, with progress strongly linked to advances in observational capability. Although many experimental approaches have borne fruit, of particular note has been the advent of millimeter and sub-millimeter study of molecular clouds at varying stages of collapse. This has given unprecedented access to phenomena at the early-to-intermediate stages of cloud collapse and central condensation onto a embryonic core. Following the categorization of André (1994), the envelopes around these class 0/I protostars dissipate to reveal a class II system in which the active accretion disk is feeding onto the central star. Such sources have now emerged in the infrared, and exhibit a number of the most interesting and enigmatic phenomena associated with young stars: active accretion, disk structure, bipolar jets and possible gap clearing.

It is important to note, however, that the stage upon which the most interesting physics is played out has now shrunk to AU scales. From an observational point of view, resolving structure at a scale of 1 AU at distances to nearby, populous star forming regions (e.g. Orion) leads to the requirement of ~200 m baselines in K-band. Fortunately, this formidable requirement will be met by the present generation of optical/infrared long baseline interferometers. It is hoped, therefore, that these devices can pick up the story where the millimeter work leaves off, and the enormous promise of fundamental new breakthroughs in our understanding, as already demonstrated in the millimeter, will be possible in the infrared and optical (hereafter, "optical" refers to both optical and infrared wavelengths).

Here we briefly review present contributions and future potential of long baseline optical interferometry to address a range of problems in contemporary young stellar object (YSO) physics. Overviews and technical discussion of optical interferometry can be found in Shao and Colavita (1992), Quirrenbach (2001) and Monnier (2003), while an excellent discussion of YSO astronomy with interferometers is given in Malbet (2002).

2. Long Baseline Optical Interferometry

Although it has a long history of varying fortunes (see Lawson 2000 for a historical development), optical interferometry is undergoing a modern flowering with a number of new instruments just now being completed. In common with other telescopes, there is great diversity of approach in design, and there are a number of fundamentally different operational modes which may be used to study astrophysical targets in quite disparate ways.

2.1. Basic Elements

In common with radio and millimeter interferometers, optical interferometers collect radiation at separate locations on the wavefront and extract information on the coherence properties of the light. Radio interferometers do this by means of a heterodyne scheme, in which the light is mixed with an artificially generated reference signal, with interference being recorded between these "intermediate frequency" components. With the notable exception of the Berkeley Infrared Spatial Interferometer (ISI), optical interferometers depart from this and utilize instead homodyne detection in which the light from the separate receivers is brought to a common location for interference with no intermediate stage. The requirements for doing this pose considerable engineering challenges, yet also allow new and interesting possibilities for operation.

Perhaps the single most difficult problem in the operation of a ground-based optical interferometer is to overcome the detrimental effects of the turbulent, inhomogeneous atmosphere. Even at an exceptional mountain-top site with good seeing, the incoming wavefront can be phase-unstable on timescales of milliseconds and on length scales of centimeters. These properties have the effect of placing limits on operation for faint targets: a sufficient number of photons must be collected to recover the phase stability of the interferometer, either from the target or (if one is lucky) a nearby bright reference.

As a very brief description, optical interferometers consist of two or more telescopes for gathering the starlight. In addition to the usual requirements for pointing and tracking, these are usually fitted with some form of adaptive optics (at least of low order) to help stabilize the incoming wavefront over the input aperture. The next subsystem encountered in most devices is an optical delay line whose purpose is to equalize the pathlength in each arm of the interferometer with a precision of the same order as the wavelength of the light. One way to visualize why this is necessary is to consider that quantum mechanical interference (fringes) will only occur when the observer cannot distinguish by which aperture a given photon entered, leading to the requirement that the traverse time must be the same for all paths to the star. This zero path difference or *array phase center* will vary as the baseline moves with respect to the star, and as atmospheric fluctuations vary the delay above each telescope. Finally, the light is combined to form interference fringes. This can be done in a variety of ways: in the image plane or pupil plane, using a beamsplitter or fiber combiner. Conceptually, however, the various ways of beam combination and fringe encoding all deliver complex visibilities for analysis.

2.2. Visibilities

Visibility amplitudes have formed the basic observable used throughout interferometry. A single visibility datum (if the object is resolved) is sufficient to constrain simple brightness models, for example uniform disks. More complete coverage of the two-dimensional visibility function can be obtained by adding more array elements or by exploiting earth-rotation synthesis with existing baselines. With higher degrees of filling of the UV plane, increasingly complex models (images) can be constrained, however without simultaneous phase recovery (see next section) ambiguities will always remain.

Despite this, most of the results to date from long baseline interferometers have come from phaseless visibility data, usually with highly incomplete Fourier coverage. Angular sizes, simple elongations or the presence of extra point components can all be relatively easily divined from limited visibility data.

One common augmentation to extend the utility of interferometric observations is to record data from a number of wavelength channels – sometimes from different spectral regions entirely. This can be used to effectively increase the baseline coverage, as long as some assumptions about the wavelength-dependent size of the target can be made.

2.3. Phase Recovery

There are a number of strategies employed to recover usable phase information despite the inherent wavefront instabilities. The most commonly used technique to date has its origins in early radio astronomy, and is known as *Closure Phase* as it consists of taking the sum of baseline phases around a closed triangle. It can be shown that this observable is not corrupted by fluctuations associated with any one receiver.

Closure phases (or if they are available, phases) can be combined with visibility data to recover an image of the object under study. It is beyond the scope of this overview to detail this process, however conceptually it entails finding ways to fill in the gaps in knowledge of the Fourier data (both interpolation and extrapolation), and of ensuring that the reconstruction adequately fits the data and is consistent with physical constraints. Image recovery fits within the mathematical domain of *inverse problems*, and unfortunately there is generally no unique solution so that some scheme must be devised to choose from among the set of viable solutions. This process is known as *regularization.*

Phase information can also be recovered as a differential quantity between separate wavelength channels. The absolute phase remains unknown, however the change in phase with wavelength can yield considerable astrophysical insight. In particular, this method is being exploited to attempt to detect faint companions (e.g. brown dwarfs or planets) in the presence of bright primary stars.

2.4. Astrometry

Interferometry can also be used to perform extremely precise astrometric measurements. If the two stars are both within the primary beam of the input telescope, the projected separation can be found by measuring the difference in optical delay between the two fringe packets. For extremely close pairs, it may be possible to do this with only one delay line, but more commonly a larger delay offset will be achieved by splitting the light from the two stars for at least a part of the optical path. The most hotly pursued application for narrow-angle astrometry is the detection of reflex motions caused by unseen companions.

Wide-angle astrometric experiments giving absolute positions on the sky can also be designed, however considerable effort needs to be invested in metrology of the optical surfaces to accomplish this.

2.5. Nulling

Nulling is the interferometric analog of coronography; the phases of incoming beams are adjusted so as to destructively interfere in one output port. This has the result that a bright object at the phase center will be extinguished, but light from any faint nearby companion not at the phase center may pass through. This has obvious applications in characterizing faint circumstellar structures such as planets or dust.

3. Overview of Results

Only the most basic operational modes of interferometers have been touched on in the preceding sections, and many refinements and observational schemes are being devised all the time. However, from the perspective of the current status of observational research into young stellar objects with interferometry, the story can be considerably simplified as the field is in its infancy and only a small number of observations published.

The first published long-baseline interferometric observation of a YSO was that of FU Ori in Malbet et al. (1998). The size was in agreement with expectations, although this star is the prototype of a small class of unusual objects thought to be dominated by accretion luminosity.

Intermediate and high-mass YSOs have been particularly amenable to interferometric study due to their high luminosities and large apparent sizes. The IOTA interferometer has been particularly productive, producing a sample of 15 Herbig Ae/Be stars (Millan-Gabet et al. 1999; 2001). These were found to be much larger than expected from simple power-law thermal accretion disk models. Puzzlingly, the sample seemed to yield no evidence for departures from circular symmetry, as would be expected from randomly inclined disks.

An explanation for the mismatch between the expected and measured sizes was arrived at independently by Tuthill et al. (2001) and Natta et al. (2001) by identifying the inner edge of a dust-free cavity to lie at the thermal sublimation radius as set by radiative equilibrium from the central star. Monnier & Millan-Gabet (2002) put this idea on secure foundations with a study of all published Herbig Ae/Be and T Tauri sizes, finding that they were consistent with expectations from the dust sublimation model. Their plot showing the recorded

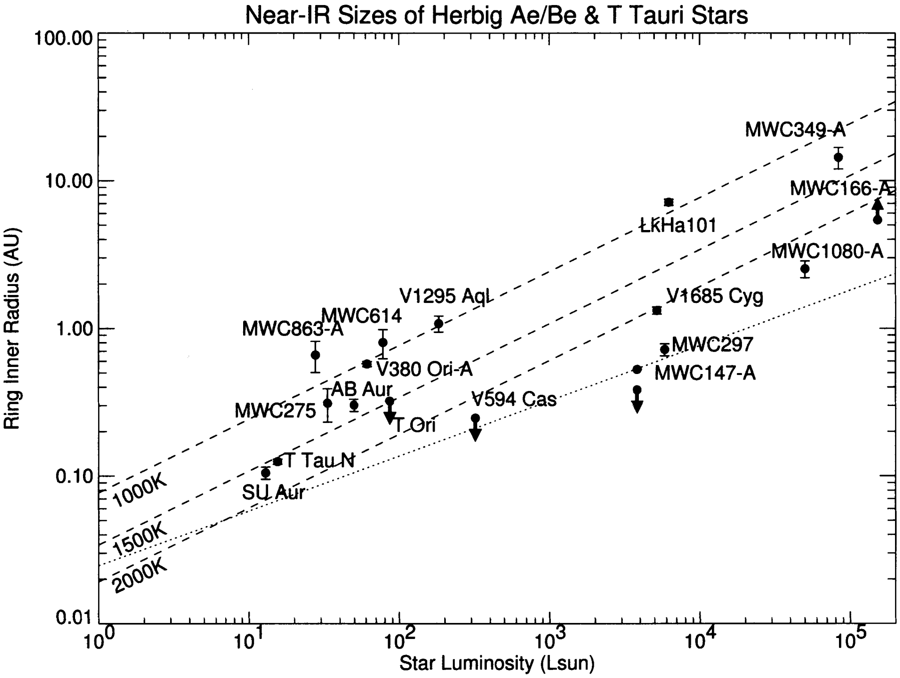

Figure 1. Size-luminosity plot taken from Figure 1 of Monnier & Millan-Gabet (2002). The dashed lines indicate expected sizes for dust at various temperatures within the region of the sublimation temperature. See original paper for details.

sizes as a function of stellar luminosity is reproduced in Figure 1 and provides an excellent overview of the current observational status of the field.

The smaller sizes of the T Tauri population have resulted in the necessity for longer baselines, and the PTI interferometer has published most of the results on this class of objects to date (Akeson et al 2000, 2002). Again, sizes were found to be larger than expected from classical thin accretion disk models. Findings on the symmetry of the small sample population studied were equivocal; some evidence for departures from circular symmetry was noted, but more Fourier coverage is needed.

Full imaging is required to remove ambiguity introduced by model-dependent interpretations as are required when Fourier data is sparse. Although a number of arrays are now almost at the point of producing images, a tantalizing foretaste of future prospect has been provided by the aperture masking experiment at the Keck telescope (Tuthill et al 2000). This has the advantage that it can provide highly complete Fourier data although the baselines are long enough to resolve only the very largest few objects. The massive emission-line object MWC 349a was found to present a high degree of elongation consistent with an edge-on view onto a circumstellar disk (Danchi, Tuthill & Monnier 2001).

Perhaps the most complete image recovered to date of the innermost hot regions of a massive YSO are those of LkHα 101 (Tuthill et al. 2001, 2002) which was found to exhibit an almost circular face-on disk structure with a central depression or cavity. This was the first direct image of such a structure, and it was found that the inner radius of the cavity was consistent with the dust sublimation mechanism. Intriguingly, a sequence of observations spanning more than two years (reproduced in Figure 2) showed some evolution of the morphology of the asymmetric brightening evident in the ring. It is fascinating to speculate that these may be the first pictures of structures within the disk such as density waves or possibly some disruptive effect due to the presence of the close companion. Hopefully, images such as these of one of the largest and brightest YSOs in the near-IR give a foretaste of the capability of the larger, more powerful imaging arrays now coming on-line which will have access to hundreds of systems.

More advanced observational modes, and coverage of new wavelength regions has also recently been reported with Hinz et al (2001) finding four YSOs to be unresolved in the mid-IR by use of nulling interferometry, and Tuthill et al (2002) reporting the first mid-IR size measurement (LkHα 101) by use of the heterodyne ISI interferometer at 11 μm.

4. Conclusions

The emerging technology of optical and infrared interferometry has demonstrated the potential to revolutionize our understanding of the mid to late stages of the star formation process. Many new facilities are poised to begin full scientific output making this an ideal time for the YSO community benefit from these new experimental endeavors.

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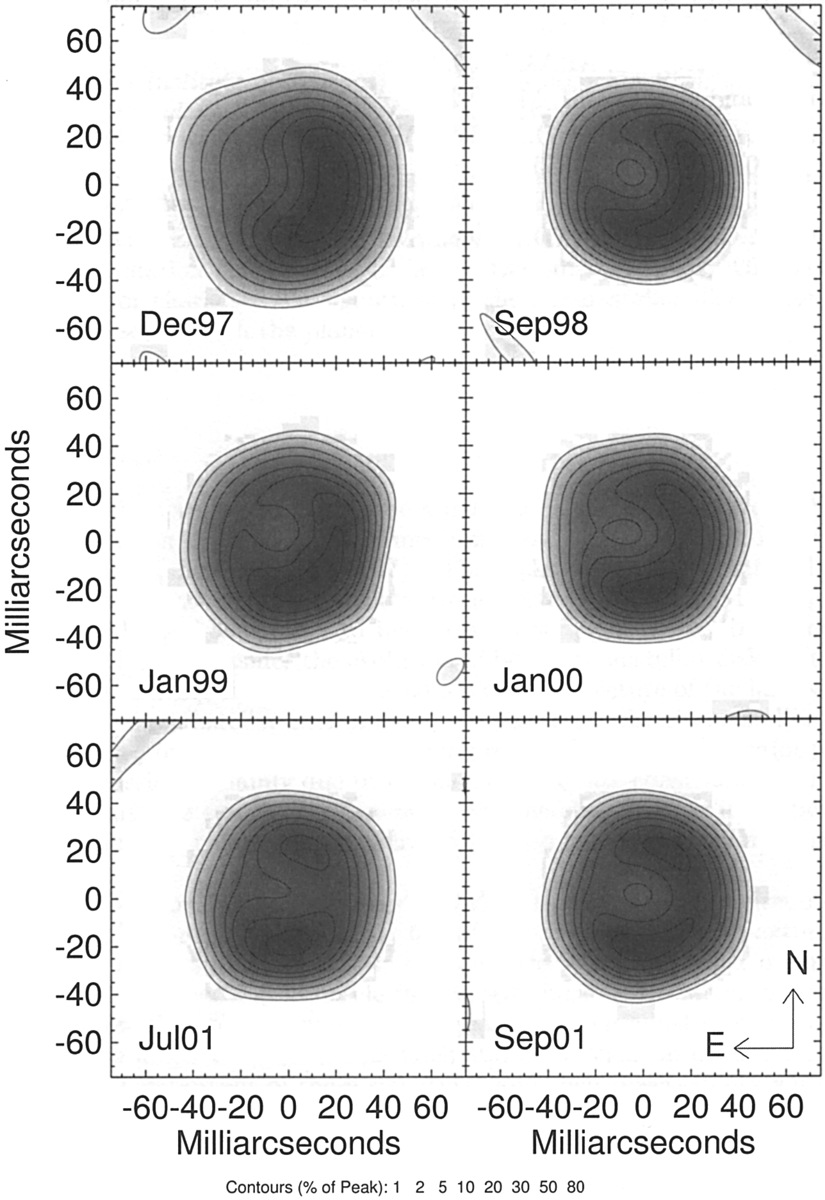

Figure 2. High resolution images of LkHα 101 in the K band taken over 6 separate epochs taken from Tuthill et al. (2002).

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