High spatial resolution multiwavelength observations of star and planet formation

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Abstract. We discuss the importance of multiwavelength (optical, infrared, millimetre, and radio), high angular resolution (arcsec to subarcsec) observations in studying star and planet formation. We provide a few illustrative examples, and briefly discuss how future observational facilities will allow a yet more detailed view of the important processes at work.

1. Introduction

The near environment of a young star is complex and dynamic. Gas and dust accretes from the parent molecular core via a circumstellar disk, where a planetary system may be forming. Simultaneously, highly-collimated bipolar jets and outflows drive some of that material away again. The star is likely part of a binary system, and/or in a dense cluster interacting with hundreds of other stars, perhaps including massive stars with intense ionising fluxes and winds.

The initial stages of cloud fragmentation and collapse can be studied with relatively low angular resolution single-dish millimetre telescopes, but once a protostar has formed with its attendant disk, jet, outflow, and nearby companions, higher angular resolution observations become vital. For example, the 60 AU diameter of our own solar system (to Neptune) would subtend less than 0.5 arcsec at the nearest star-forming regions, the low-mass dark clouds (*e.g.,* Taurus-Auriga at ~ 140 pc), and less than 0.15 arcsec at regions of massive star formation in the Orion giant molecular clouds (~ 500 pc). In addition, there is a wide range in temperature (~ 10–10000 K) and associated dust extinction ($A_V \sim 0^m$–1000^m) involved. Thus, to have a hope of disentangling the various formation and evolution processes at work, high angular resolution observations at optical, infrared, millimetre, and radio wavelengths are necessary.

Such observations are now routinely available and in this contribution, we shall present just a few (and as a consequence, mostly personally biased) recent case studies to illustrate the importance that (sub)arcsec angular resolution has in furthering our understanding of star and planet formation. We shall also briefly mention future advances in instrumentation that should allow us to make further significant breakthroughs in the coming decade. A more detailed review of recent star and planet formation observations carried out with large (8–10m class) optical/infrared telescopes, and of high-resolution imaging of very low-mass stars, brown dwarfs, and circumstellar disks in the Orion Trapezium Cluster can be found in McCaughrean (2000, 2001) respectively.

2. The jet–outflow connection: the case of HH 211

Young stars go through a phase where they eject bipolar outflows of cold molecular gas seen at millimetre wavelengths (Fukui *et al.* 1993) and in some cases, highly collimated jets of ionised and/or shocked molecular gas seen at optical/infrared wavelengths (Hartigan *et al.* 2000). One theoretical model holds that a magnetohydrodynamic X-wind directly drives the broader outflow and also asymptotically converges to form a jet along the central axis (Shu *et al.* 2000). Another suggests that the jet is the prime mover, and that it entrains the outflow as it impacts the surrounding molecular medium (Raga & Cabrit 1993). Problems in distinguishing between these two models arise in part due to the large difference in spatial resolution afforded by single-dish millimetre observations of the outflow ($\gtrsim 10$ arcsec) and optical/infrared imaging of the jet ($\lesssim 1$ arcsec). However, the advent of sensitive arcsec resolution millimetre interferometry has begun to clarify matters.

HH 211 is a highly collimated jet associated with a very young Class 0 protostellar system near IC 348 in Perseus (McCaughrean, Rayner, & Zinnecker 1994). The jet is seen only at infrared wavelengths, most notably in emission from shocked molecular hydrogen at 2.122μm, and exhibits a peculiar bilateral symmetry about the axis of an associated cold molecular outflow. The jet is only ~ 0.15 pc long and thus probably only $\sim 10^3$ yrs old, assuming typical jet velocities of 100–$200\,\mathrm{km\,s^{-1}}$. As such, it is an ideal system in which to study the initial interaction of the jet with its surrounding medium.

Gueth & Guilloteau (1999) were able to image HH 211 at arcsec resolution in the ^{12}CO (2–1) line using the Plateau de Bure millimetre interferometer (Figure 1). They found that the cold outflow is essentially coextensive with the shocked H_2 of the jet, and that at low velocities, the CO emission is almost directly coincident with the H_2 knots and thus bilaterally symmetric. At high velocities however, the CO is confined to a narrow jet down the centre of the H_2 structure. This spatial and velocity structure can be well understood in terms of the Raga & Cabrit (1993) model, in which the bowshock of the underlying highly collimated jet interacts with the ambient medium, and entrains cold ambient gas into an outflow. Thus at the very young age of HH 211 at least, it appears as though the jet-driven outflow paradigm applies.

Further complementary optical/infrared and millimetre studies of jets and outflows as a function of age and luminosity are needed to extend this finding: sensitive wide-field, high-resolution optical/infrared imaging is available with the new 8m-class telescopes (*e.g.*, VLT, Gemini, Subaru, Keck), while the millimetre and submillimetre observations will be possible with the SMA and ALMA.

3. Extraction of angular momentum: the case of HH 212

As a perhaps inevitable side effect of star formation, jets and outflows can also play an important part in the process. Excess angular momentum must be shed from infalling molecular core material if any of it is to be accreted onto the central star. Viscous processes in the circumstellar disk may transport some angular momentum outwards, but a rotating jet and outflow may satisfy the same goal.
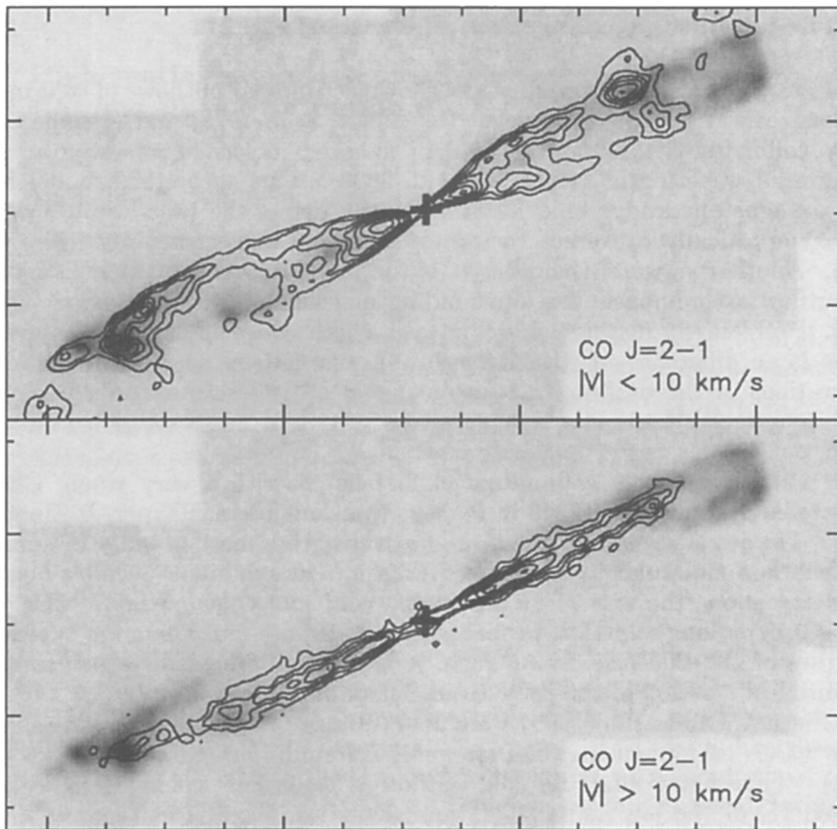
Figure 1.   The HH 211 jet and outflow in Perseus. The jet is seen in grayscale in both panels in shocked molecular hydrogen at $2.122\mu m$ (McCaughrean, Rayner, & Zinnecker 1994), exhibiting a peculiar bilateral symmetry. The contours show ^{12}CO (2–1) emission (Gueth & Guilloteau 1999). The top panel shows low velocity CO emission largely coincident with the H_2 structures, thus tracing the zone where the jet is interacting with the ambient medium and entraining it. The lower panel shows high velocity CO gas tracing out the true jet itself.

Until recently however, there has been almost no evidence for rotation in jets, so no angular momentum balance calculations have been possible.

HH 212 is another very young jet seen only in shocked H_2 emission at near-infrared wavelengths, and is associated with a Class 0 protostar in Orion (Zinnecker, McCaughrean, & Rayner 1998). The jet is highly symmetric, with a series of knots and bowshocks on one side that is almost exactly mirrored by an equivalent set on the other, the jet stretching over 0.4 pc in total length (Figure 2). The implication of this symmetry is that the sequence of knots and bowshocks must be related to intrinsic variations at the star itself, a kind of ticker-tape record of its accretion history. Proper motion measurements in
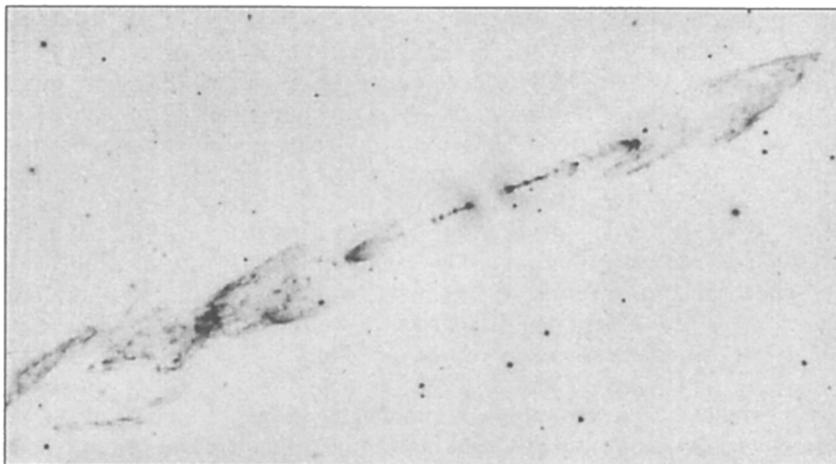
Figure 2.   The HH212 jet seen in the 2.122μm line of molecular hydrogen. The jet exhibits a high degree of symmetry in the series of knots and bowshocks seen on either side of the embedded driving source. These data were taken with the infrared camera ISAAC on the 8.2m VLT in October 2000. The integration time is 90 minutes for most of the jet, 45 minutes for the outer bowshocks; the resolution is seeing-limited at 0.35 arcsec FWHM (McCaughrean *et al.*, in prep).

HH 212 show tangential velocities of ~ 100–$300\,\mathrm{km\,s^{-1}}$, both in the innermost knots as seen in H_2 (McCaughrean *et al.*, in prep), and at the base of the jet as seen in VLBA observations of H_2O masers (Claussen *et al.* 1998). Small differences in radial velocities on the two sides of the jet show that it lies within a few degrees of the plane of the sky (Zinnecker *et al.* 1998; Claussen *et al.* 1998).

At high spatial resolution in the near-infrared, the innermost H_2 knots are resolved into small bowshocks, with sizes typically 1 arcsec ($\sim 400\,\mathrm{AU}$) transverse to the outflow direction. Davis *et al.* (2000) carried out velocity-resolved spectroscopy in the 2.122μm line to measure the radial velocities of the knots at three spatial positions transverse to the outflow axis. The spectra showed evidence for a systematic radial velocity gradient of $\sim 2.3\,\mathrm{km\,s^{-1}}$ over ~ 1 arcsec (400 AU) across some of the knots, which Davis *et al.* tentatively interpreted as being due to rotation in the jet.

At the same time, Wiseman *et al.* (2001) used the VLA in the NH_3 (1,1) line to map the velocity structure of the large-scale (12000 AU FWHM diameter) flattened envelope from which the driving source of HH 212, IRAS 05413−0104, is probably still accreting. They found a smooth, constant $\sim 0.2\,\mathrm{km\,s^{-1}}$ radial velocity gradient over ~ 22 arcsec (8800 AU) transverse to the outflow axis, indicative of solid-body rotation at least in outer parts of the envelope: the Keplerian rotation that most probably exists further in may well be masked by optical depth and resolution effects.

The first important point is that the H_2 and NH_3 velocity gradients show that the jet and envelope rotate in the same sense. The second point is that the

jet may indeed be able to carry away much of the envelope angular momentum. First we assume that the jet rotates at $1.15\,\mathrm{km\,s^{-1}}$ at a radius of 200 AU (*i.e.*, $2.3\,\mathrm{km\,s^{-1}}$ over 400 AU). Then the fraction of the disk mass that must be carried away by the jet in order to remove *all* of its angular momentum is given by the ratio of the disk velocity at 200 AU radius to that of the jet. At one extreme, if we assume the apparent solid-body rotation in the NH_3 core continues in to 200 AU, then the velocity there would be $0.005\,\mathrm{km\,s^{-1}}$. In this case, only $(0.005/1.15) \sim 0.5\%$ of the disk material would have to be ejected in the jet. At the other extreme, assuming an underlying Keplerian rotation from the outer edge of the NH_3 core inwards, the velocity at 200 AU would be $\sim 0.47\,\mathrm{km\,s^{-1}}$. Then $(0.47/1.15) \sim 40\%$ of the disk material would have to be in the jet.

Clearly these are very crude approximations, and the reality must be much more complicated. Nevertheless, HH 212 appears to provides at least broadly plausible evidence that the angular momentum problem may be solved by converting some fraction of the infalling material into a relatively rapidly rotating outflowing jet. Obviously however, these results are very preliminary, and substantially better rotation curves must be obtained both for infalling envelopes and disks, and their corresponding outflowing jets. The VLA and ALMA will provide the former data, while echelle spectrometers coupled with adaptive optics on large 8m-class telescopes will provide the latter.

4.   Direct imaging of circumstellar disks

The present paradigm for star formation holds that planets form in dense disks of dust and gas. But despite ample evidence for such disks encircling young stars on one hand and for extrasolar planetary systems around nearby mature stars on the other, it is still not really known how these disks turn into planets, or at what efficiency, *i.e.*, what fraction of all disks indeed develop planets. The fact that the discovery of massive planets in very close orbits around nearby stars was a surprise, indicates that this problem cannot be solved on the basis of theory alone; observations of the evolution of disks are needed.

Typical circumstellar disks have diameters of $\lesssim 500\,\mathrm{AU}$, and subarcsecond resolution is required to make detailed probes of their structure in the nearest star-forming regions. It is now possible to resolve the cold gas and dust in nearby disks via millimetre interferometry (Wilner & Lay 2000), but even higher resolution is available at optical/infrared wavelengths via the HST and adaptive optics. At these wavelengths, we are sensitive to scattering and absorption by dust (McCaughrean, Stapelfeldt, & Close 2000).

A particular case in point are the disks seen around young stars in the Trapezium Cluster, in silhouette against the bright emission-line background of the Orion Nebula (O'Dell, Wen, & Xu 1993; McCaughrean & O'Dell 1996; Chen *et al.* 1998; McCaughrean *et al.* 1998; Bally, O'Dell, & McCaughrean 2000). Figure 3 shows an HST montage of these disks, spanning a wide range of sizes and orientations. Several disks are seen edge-on, where if the central star is seen at all, it is via polar reflection nebulae, not directly, thus minimising contamination by direct stellar light.

Multiwavelength optical/infrared imaging of these edge-on disks can be used to probe their structure and dust properties at the outer edge. The disks are
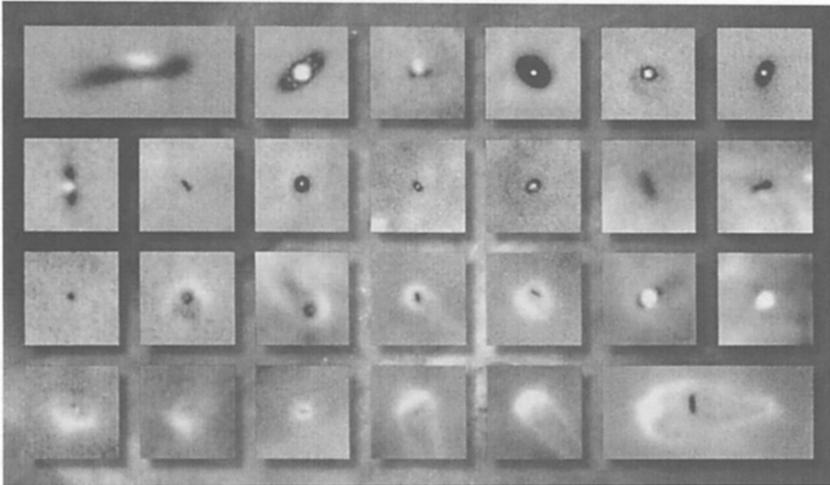
Figure 3.   HST images of young silhouette disks in the Orion Nebula, associated with young (0.5–2 Myr) low-mass (0.3–1.5 $M_\odot$) members of the Trapezium Cluster. Some of the disks are near edge-on and the central star cannot be seen directly; some others are embedded in ionised nebulae created as the disk is heated and ablated by the central OB stars in the cluster. Each panel is 1.67×1.67 arcsec or 750×750 AU in size (the two large panels are 1700×750 AU); disk radii are $\sim$ 50–500 AU. The images were taken in the Hα filter of WFPC2 or the [O III] filter of STIS (from McCaughrean & O'Dell 1996; Bally, O'Dell, & McCaughrean 2000).

sharply truncated at some outer radius, but nevertheless have resolvable structure there (McCaughrean & O'Dell 1996). Throop *et al.* (2001) have recently suggested that the apparent lack of change in transparency between 0.5 and 1.9μm at the edge of the large (900 AU diameter) edge-on disk Orion 114-426 is evidence for achromatic and thus large dust grains, with diameters of 5μm or greater, as compared to typical ISM grains at least ten times smaller. They present modelling results which suggest that if grain growth has proceeded to this degree at the outer edge, there should be significantly larger millimetre- and even metre-sized rocks further in, where the disk is denser. In turn, this would suggest that planetesimals may form rather quickly and that planetary systems may already be developing in these $\sim$ 1 Myr old disks. This result contrasts with that from HST imaging of similar edge-on disks seen around stars in Taurus-Auriga (*e.g.*, HH 30: Burrows *et al.* 1996; HK Tau/c: Stapelfeldt *et al.* 1998), where little evidence for grain growth is seen.

In any case, the majority of the circumstellar disks in the Trapezium Cluster are being externally photoevaporated by the central OB stars, with the hot gas then forming a ionised bubble around the young parent star. The destruction timescale for these disks is thought to be rather short ($\sim 10^5$ yrs; Hollenbach, Yorke, & Johnstone 2000), and even if large grains have formed already, the disks may not survive long enough to form mature planetary systems.

More detailed studies of the structure and evolution of disks in hazardous environments are needed, since the bulk of the galactic stellar population may form in such regions. Substantially higher resolution optical/infrared imaging will become available with ground-based adaptive optics (*e.g.*, NAOS/CONICA on the VLT), space-based imaging (NGST), and, ultimately, interferometers (*e.g.*, VLTI, LBT, Keck; *cf.* Malbet *et al.* 1999). A detailed examination of disk structure as a function of age and environment should yield important clues as to how disks may (or may not) form planetary systems.

5.   Young stellar clusters

Thus far we have largely been discussing isolated stars, their jets, and their disks. However, a large fraction of the galactic field population is thought to form in dense, embedded clusters (Lada, Myers, & Strom 1993), and thus a detailed assessment of their cumulative properties and the effects of such a crowded birth environment is vital if we are to understand the processes by which whole populations of stars form.

These clusters can have stellar densities of up to 10^4 to 10^5 stars per cubic parsec in their cores, yielding a typical projected linear separation of $\sim 1000\,\mathrm{AU}$, or just 2 arcsec at 500 pc and only 0.4 arcsec at a more typical distance of 3 kpc. In addition, there is often strong background emission from an H II region and significant associated dust. Thus high angular resolution infrared imaging is a prerequisite for separating individual stars, and for detecting faint, low-mass cluster stars and brown dwarfs close to brighter companions, against the nebular background, and through the extinction. As a concrete example, a 2 Myr old $1\,\mathrm{M_{Jup}}$ object with $A_V \sim 10^{\mathrm{m}}$ in a nearby star-forming regions at 150 pc would have a K-band magnitude $\sim 20^{\mathrm{m}}$, and could be detected in a few hours with good subarcsec imaging on an 8m class telescope.

Space constraints here preclude a detailed look at any recent results from young cluster studies. However, as a representative example, the importance of high angular resolution was highlighted in a VLT study of the distant (6–7 kpc) cluster NGC 3603 by Brandl *et al.* (1999). Even at this distance, the large collecting area of the VLT and excellent seeing on Paranal (0.4 arcsec FWHM) made it possible to resolve and detect stars down to $0.1\,\mathrm{M_\odot}$, just above the hydrogen burning limit, in 45 minutes. Similarly deep, high angular resolution infrared imaging surveys have also been obtained of the Trapezium and RCW 38 clusters with the VLT (McCaughrean 2001; Alves *et al.*, in prep). This will remain a very fertile area in the years to come, using the 8m class telescopes for deep imaging surveys, followed up with multiobject classification spectroscopy (*e.g.*, VIMOS/NIRMOS on the VLT), and even detailed proper-motion studies to ascertain cluster dynamics (*e.g.*, PRIMA on the VLTI). The extraordinary sensitivity and wide-field diffraction-limited imaging capability of the NGST will extend these studies to very low mass limits right across the galaxy.

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