Stellar Jets with OSIRIS and GMOS: Integral Field Spectroscopy of Outflows from Young Stars

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AO integral field spectroscopy is an exceptionally powerful tool for studies of outflows from young stars, providing information on velocities, collimation, proper motion, and physical conditions within jets. We present multi-epoch Keck OSIRIS + Gemini GMOS IFS observations of the jet from LkHa 233, which provide the most detailed picture yet of an outflow from an intermediate-mass star. This fall, observations are planned for additional outflows including the nearby TTS BP Psc and young embedded sources in Taurus.

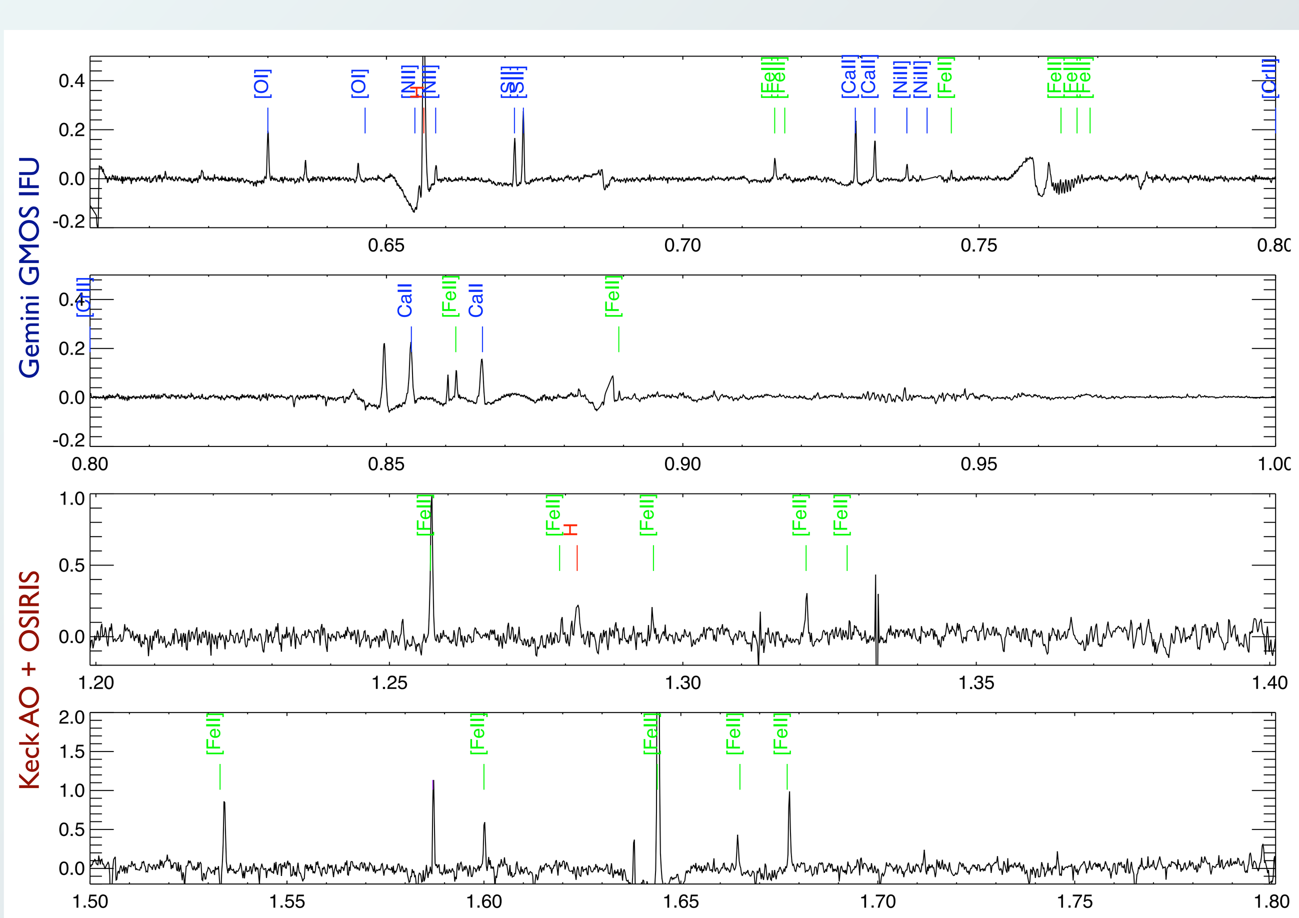
Why study stellar outflows with IFUs?

Bipolar jets from young stars play a crucial role in angular momentum transfer and powering of molecular cloud turbulence, but the underlying physical mechanism remains mysterious. High angular resolution observations close to their origin allows us to measure their structure and kinematics in detail, thereby helping discriminate between possible jet launch mechanisms (e.g. Shu et al. (1994); Shang (2006); Konigl & Pudritz (2000); Pudritz (2006).)

The required observations combine high angular resolution with moderate spectral resolution, making them a perfect match for AO integral field spectroscopy. Until/unless STIS is repaired, AO IFS is the only technique which can obtain such data on scales of a few AU.

With OSIRIS+LGS AO shared-risk observations in fall 2005, we obtained the first-ever high angular resolution imaging spectroscopy of an outflow from a Herbig Ae star, LkHa 233 (Perrin & Graham 2007, ApJ in press). These data enabled us to measure the mass flux, $(1.2 \pm 0.3) \times 10^{-7}\ M_\odot$/yr, collimation and velocity of the outflow, and revealed intriguing asymmetries.

Measurement of Physical Conditions Within Jets



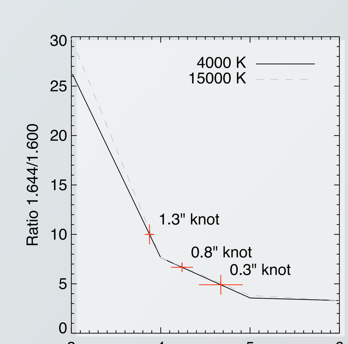


Figure from Perrin & Graham 2007

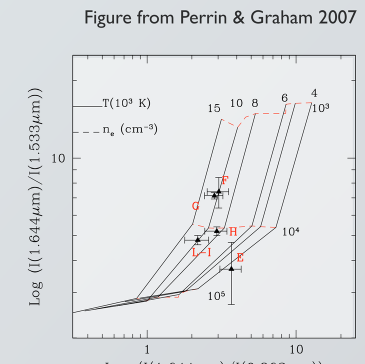


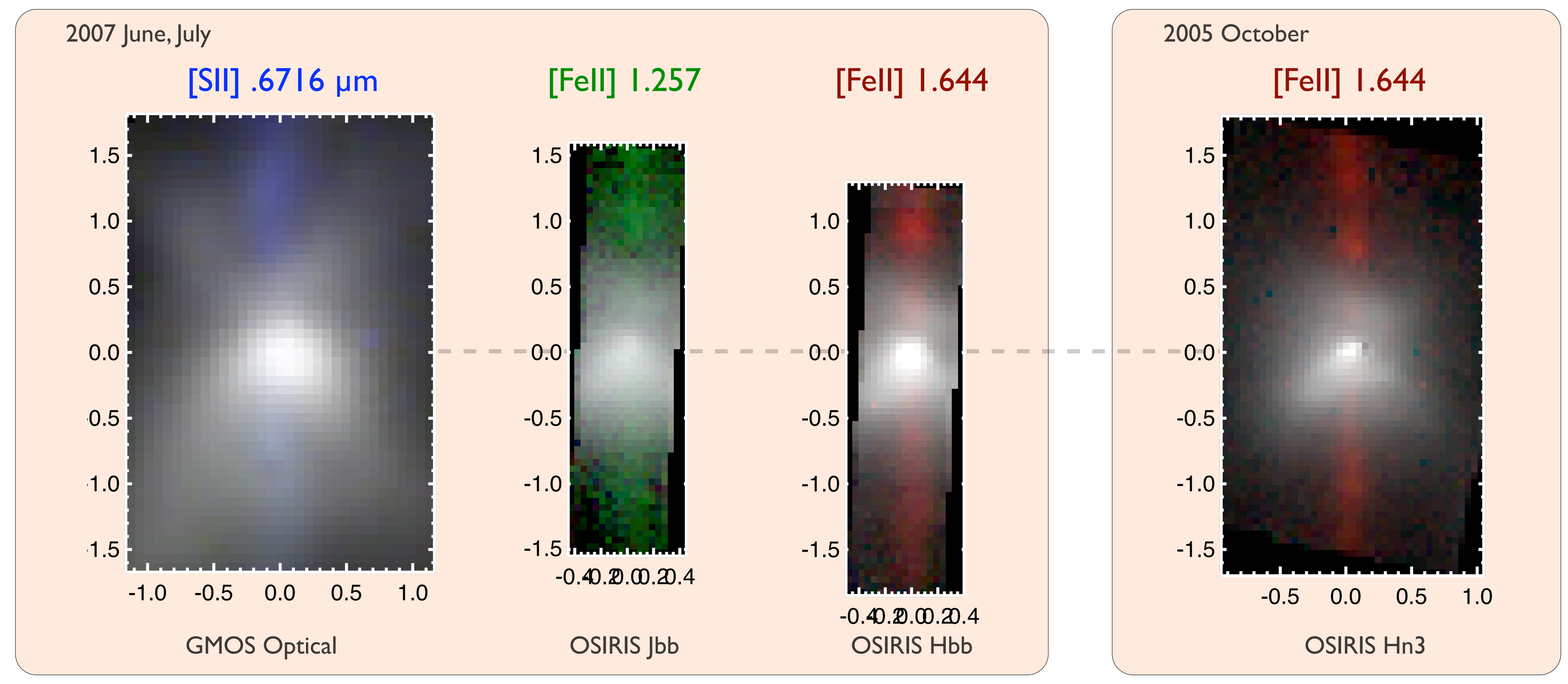
Figure from Nisini et al. 2005

Left: Spectrum of knot A in LkHa 233's jet. **Above:** Example measurements of temperature and electron density using optical and infrared lines of [FeII].

Jets are seen primarily in a number of shock-excited optical and infrared emission lines, including most prominently [OI] 6300, 6364 Å, [SII] 6716, 6732 Å and [FeII] 1.257, 1.644 μm, among many others. Recently, it has been recognized that the diagnostic potential of optical and near infrared spectra together far exceeds that of either spectral region taken alone (Nisini et al. 2005; Podio et al. 2006). Optical/IR line ratios allow measurement of density, temperature, ionization and excitation, extinction, depletion of refractory elements onto grains, and ultimately mass flux, a key quantity for constraining models.

By obtaining combined optical/NIR integral field spectroscopy of the LkHa 233, we can now for the first time apply this technique to a jet from a Herbig Ae star. Analysis is still ongoing, but our present data promise to provide the most detailed knowledge yet of an intermediate mass star's outflow.

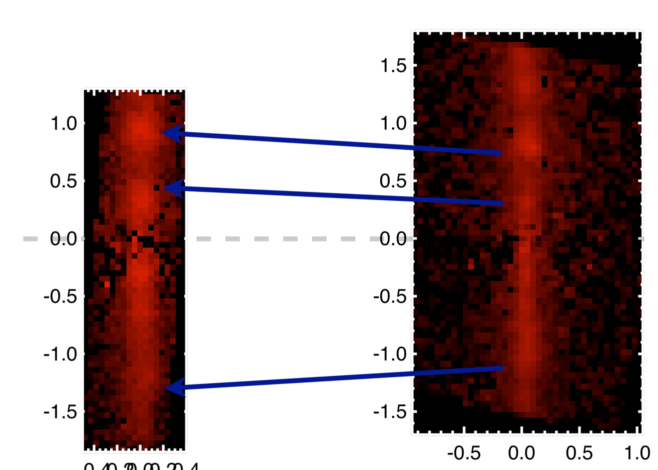
Combined Optical / Near IR Imaging Spectroscopy



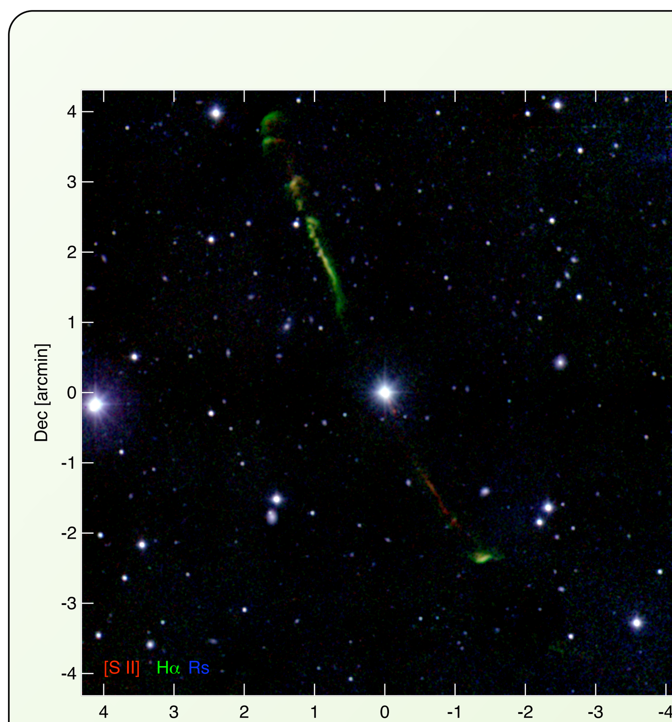
To improve on our initial study of LkHa 233's outflow, we have very recently obtained near-simultaneous optical and IR imaging spectroscopy using OSIRIS plus GMOS on Gemini North. With these combined spectra covering dozens of lines from 0.6-1.8 μm, we can obtain a complete picture of the physical conditions inside this outflow, including key quantities that can be used to test the X-wind and disk-wind theories (see below left).

These spatially and spectrally resolved data also allow measurement of jet dynamics (velocity, acceleration, collimation, and anisotropies), and now with two epochs we can measure proper motions. Combined with radial velocities and the estimated inclination, this will give the true space velocity and/or an independent estimate of distance.

Above: Narrow-band images extracted from IFS datacubes show the jet in several shock-excited emission lines. The continua are shown in grey, and the various plots are sized and located correctly for their fields of view relative to the centroid of LkHa 233 itself. **Right:** Continuum-subtracted versions of the H-band data, showing the [FeII] 1.644 line on two epochs 1.8 years apart. Outward motions of the knots and clumps are apparent in both the red- and blue-shifted outflows. The observed proper motion of ~0.1″/year supports the closer distance of ~420 pc to LkHa 233 advocated in Perrin & Graham (2007).



What's Next?



Above: BP Psc is an intriguing star newly-identified as a very nearby yet unusual classical T Tauri star (Zuckerman et al., ApJ submitted). While it appears to be a usual ~10 Myr CTTS in many respects, a weak Li 6709 A line is inconsistent with an age < 100 Myr.

Using Lick PFCAM, we discovered a curved bipolar outflow extends at least 0.3 pc from BP Psc. OSIRIS observations next month will provide the first high-resolution observations of this outflow, enabling studies comparable to our results on LkHa 233 (but at 5x finer spatial sampling due to its proximity). If BP Psc does turn out to be ~100 Myr, it will be by far the oldest star with such an extensive outflow. Even if not, it will still be one of the closest outflows (~100 pc), allowing details as small as 5 AU to be seen. Hence BP Psc is likely to become an especially good testing ground for detailed models of jet acceleration and collimation.

Apart from continuing our analysis of the new data presented here, we also seek to expand our observations to outflows from a wider range of stars. Detailed spectral diagnostics are available for an increasingly large set of T Tauri stars (e.g. Nisini et al. 2005, Podio et al. 2006), but these are mostly seeing-limited data (see Hartigan et al. 2007 for one exception using HST STIS).

The higher resolution of AO lets us see fine details on AU scales around nearby targets, or obtain comparable data on more distant (~kpc) targets such as Herbig Aes. But perhaps the most exciting area is using LGS AO + IR IFS to obtain high resolution observations of faint, dust-shrouded sources at the youngest ages, when accretion and outflow are greatest and mass fluxes are highest. This also opens the way for high resolution studies of outflows from high mass stars, which evolve rapidly while still embedded and optically faint. Observing how jet properties vary with mass, age, and environment is crucial to advancing our understanding of their role in the star formation process.