Lab #5:
Near-infrared adaptive optics imaging of a triple system

11/02/2010

Your report is due on November 16, 2010 at 5:59 PM PDT.

1 Overview

1.1 Background

In this lab, we will focus on imaging in the near-infrared regime (1-5 μm). While the technology of detectors is different, the basic principles of astronomical imaging remain the same as with CCD cameras: each pixel has a total number of DNs that is proportional to the incoming photons, and typical calibration operations include dark current subtraction and flat-fielding correction. Because of Wien's Law, the Earth atmosphere, the telescope and any part of the instrument that is not cooled down strongly emits in the near-infrared and background subtraction is an important step.

The second specificity of this lab is the use of adaptive optics (AO) -fed instruments. AO systems are devices that are inserted in between the telescope and the science instrument to correct for the constant blur introduced by the Earth's turbulent atmosphere. The purpose of this device is to enable diffraction-limited imaging, i.e., to discern details typically an order of magnitude finer than in normal ("direct") imaging.

Finally, the scientific focus of the lab is on a very young triple stellar system. As opposed to our own Sun, many, if not a majority, of star in our Galaxy are formed with one or more stellar companions. The processes at stake during the formation of such systems are still under debate and studying very young multiple systems can help clarifying some of the current uncertainties. In this lab, we will study T Tau, a young triple system that consists of an optically bright component (T Tau N) and an infrared bright component (T Tau S), which is itself a tight binary system (T Tau Sa and Sb). The distance to this system has been measured to be 147.6±0.6 pc (Loinard et al. 2007).

1.2 Key steps

The key steps for this lab are the following:

1) Use a first set of Keck AO images of T Tau at several wavelengths to study the wavelength dependence of the sky background and the quality of correction provided by an AO system;
2) Compute relative fluxes of all three components of T Tau and probe their physical nature compared to other young stars;
3) Compute relative positions of all three components and derive a first guess of the orbital periods involved;
4) Repeat the analysis on 3 other datasets: study photometric variability and relative motion, derive mass ratio for S component.

2 Diffraction-limited images

In normal imaging with a ground-based astronomical telescope (as in Lab 4, for instance), each star appears as a Gaussian with a FWHM of 0.5-2 arcsec typically. However, if everything was perfect, a telescope of diameter D should yield diffraction-limited images, in which the smallest distinguishable detail has a size of λ/D (expressed in radian). For instance, the diffraction limit of the Nickel telescope at V band is 0.11", well over an order of magnitude smaller than we measured in our last lab. The "imperfection" in most astronomical images is introduced by the Earth atmosphere, whose constant turbulent motion blurs the image. AO systems are devices which track down *in real-time* the effects of this turbulence and constantly apply compensating forces on a small "deformable mirror." Even though this correction is imperfect, the resulting images (if they are taken in the near-infrared regime) are diffraction-limited and allow astronomers to take full advantage of the large size of modern telescopes.

Given the typical size of a star and its distance to the Sun, virtually all stars in our Galaxy should be point-like with any existing telescope. An image of a star therefore represents the so-called point spread function (PSF), i.e., the response of the telescope+instrument to a point source. When imaging a more complex object (a multiple system, a Solar System planet or a galaxy), its intrinsic distribution of light is convolved by this PSF to produce the observed image.

Using Fourier optics to describe a full telescope, one can show that the perfect PSF of a telescope, neglecting Earth turbulence and all optics defects, is the amplitude of the Fourier Transform of the "entrance pupil". This is a function whose value is unity within the aperture (primary mirror) of the telescope and zero everywhere else. In the approximation of a filled circular aperture, the PSF is a well-known Airy function whose FWHM is roughly equal to λ/D.

AO devices produce a PSF that is imperfect: most of the light is compressed into an Airy-like function, but a fraction of the light remains uncorrected by the AO system and produces a broad pedestal whose FWHM is the atmospheric seeing. One method used by astronomers to quantify the quality of the AO correction is to compute the so-called Strehl ratio, which is the ratio of the corrected to uncorrected portion of the PSF. In practice, this is generally estimated by comparing the image of a star to that of the perfect PSF scaled to the same total flux. The Strehl ratio is computed as the ratio of the peak intensity of these two images. By definition, a Strehl ratio of 100% is a perfect correction; typical observations without AO observations have Strehl ratios well below 1%. Typical corrections obtained by current AO systems reach Strehl ratio of 50-60% at a wavelength of 2 μm.

3 Single-epoch multi-wavelength AO images

The first dataset we will use for this lab has been obtained with NIRC2 at the Keck telescope on December 12 2002. The dataset includes images taken with the K_{cont}, L' and M_s filters (centered at 2.27, 3.78 and 4.67 μm, respectively) and a 0.01"/pix pixel scale. To avoid saturation of the bright stars, the data were taken with very short integrations, large number of images coadded in a single stored file (NB: the saved images are the *sum* of all coadded images, not their *average*!)

and using a small subset of the entire array to enable fast enough readout. Table 1 provides a log of the data taken during the night.

Table 1 – Observing log of the Keck/NIRC2 AO observations on Dec 12 2002.

File #	Object	Filter	T_{int} (s)	N_{coadds}	Subarray
4–6	Dome flat-field	*K'*	30.	1	1024x1024
19–21	Dome flat-field	*K'*	30.	1	1024x1024
59–62	T Tau	*L'*	0.018	100	256x264
63	Sky	*L'*	0.018	100	256x264
64–65	T Tau	M_s	0.018	100	128x152
68	Sky	M_s	0.018	100	128x152
169	Sky	K_{cont}	0.053	100	512x512
170–173	T Tau	K_{cont}	0.053	100	512x512
413–417	Darks	–	0.053	300	512x512
418–422	Darks	–	0.018	300	256x264
438–442	Darks	–	0.008	100	128x152

3.1 Theoretical PSF

Compute the theoretical PSF for the three wavelengths of interest (use the program from Appendix 6). To obtain these data, the so-called "inscribed circle" pupil of NIRC2 was used, which is equivalent to say that the primary mirror was effectively reduced to 9m diameter. The central obscuration, through which light reaches the instrument is on the order of 1m in diameter (try a few values, including a case of no central obscuration). Compute the FWHM of the resulting images for each wavelength and plot it as a function of wavelength; compare this to the theoretical λ/D expectation.

3.2 Calibration frames

Compute a master dark image for all relevant subarrays. Note that the level of bias+drak is strongly dependent on the size of the subarray, and that the dark current rate is negligible considering the very short exposures.

Compute a master flat-field image for the K' filter, which we will apply to the K_{cont} images since these filters have similar central wavelengths (use the 1024x1024 flat field frame and crop the central 512x512). For the L' and M_s filters, no dedicated flat-field frames were taken. Instead we can use the "sky" frames, after subtracting the bias+dark level, as this is the same type of data we obtain with twilight flat-field frames.

3.3 Background level as a function of wavelength

Use the "sky" frames, corrected for the bias+dark and plot the intensity of the background flux (per second) as a function of wavelength. Discuss the resulting plot.

As a general rule, near-infrared data are analyzed by simply subtracting off a sky frame (taken with the same integration time and detector setup) from any raw image. This simultaneously corrects for the bias, dark and thermal background in a single operation, minimizing the noise.

3.4 Clean images of T Tau as a function of wavelength

Subtract the relevant sky from each image of T Tau for all three filters. Correct each image for the flat-field and, if necessary, apply a constant offset to bring the average background level to zero (rapid fluctuations of the background level are common in the near-infrared).

The data have been obtained in the so-called "vertical angle" mode, in which the orientation of the sky in the images rotates slowly during the observations. Each image is therefore rotated from the others. To bring all images in the same reference frame where North is to the top and East to the left, use the `ROT` function in IDL (note that the `ROTATE` function is different from `ROT`), knowing that the position angle of the upward vertical in a given image is given by the header keyword `PARANG`. In astronomy, position angles (PAs) are defined such that PA=0° and 90° point towards North and East, respectively, so this is measured counterclockwise in an image. One all images are oriented in the same way, shift all images obtained with a given filter so that the stars are aligned and compute the average image for each filter.

Describe the images: what do you see? Does the appearance of the stars follow the theoretical PSFs? If not, in what way do they depart from your expectations? What is the origin of these departures? Compute the FWHM of the brightest star (T Tau N) and compare to the theoretical plot computed before.

3.5 Relative astrometry and photometry

One of the goals of this lab is to determine with high precision the relative position of the three stars in the T Tau system. Which image do you think is the best one to use for this purpose? Why? Compute the position of T Tau Sa and Sb relative to each other and relative to T Tau N. When assessing the uncertainties, take into account a 0.5% relative uncertainty on the plate scale of the camera and a 0.5° uncertainty in its absolute orientation relative to the sky.

Using the known position of the stars (which are fixed over the course of the few hours of these observations), estimate the fluxes of T Tau Sa and Sb relative to T Tau N, along with associated uncertainties.

4 Multiple epochs images

4.1 Other Keck/NIRC2 datasets

Additional images of the T Tau system where taken on October 20 2008 and December 08 2009 using NIRC2 and the Keck AO system. These datasets were obtained with the Brγ filter (centered at 2.17 μm) and using the entire detector array (1024x1024). In both datasets, the data were taken in "position angle" mode, meaning that North and East are due up and left in all images. Finally, the "inscribed pupil" has not been used in either dataset, so that the spatial information arising from the entire primary mirror (up to almost 11m along the longest "baseline"). Processed flat-field frames are provided for both nights. No sky frames were taken during these observations.

Reduce both datasets (how do you estimate the background emission?) so that you have one final average image per epoch. Compare the FWHM of the PSF (measured using T Tau N) to that you obtained with the 2002 data. If they are different, why is that? Measure the relative positions and fluxes of T Tau Sa and T Tau Sb relative to T Tau N. The same uncertainties regarding the detector pixel scale and orientation can be used as for the 2002 dataset.

4.2 VLT/NaCo datasets

NAOS-CONICA (NaCo for short) is ESO's Very Large Telescope dedicated AO system and near-infrared camera. On October 11 2006, images of T Tau were taken with NaCo using the K_s (2.18 µm) filter and the 13.25 mas/pixel camera setup. The images are oriented so that North and East are due up and left, respectively. A processed flat-field frame is available, but no dedicated sky frames were taken during the observations.

Reduce this dataset and produce a final image of the system. What is the FWHM of the PSF? Is this consistent with the λ/D expectation of a diffraction-limited image? Measure the relative positions and fluxes of T Tau Sa and T Tau Sb relative to T Tau N. Use a 0.5% relative uncertainty on the plate scale of the camera and a 0.5° uncertainty in its absolute orientation.

5 Analysis

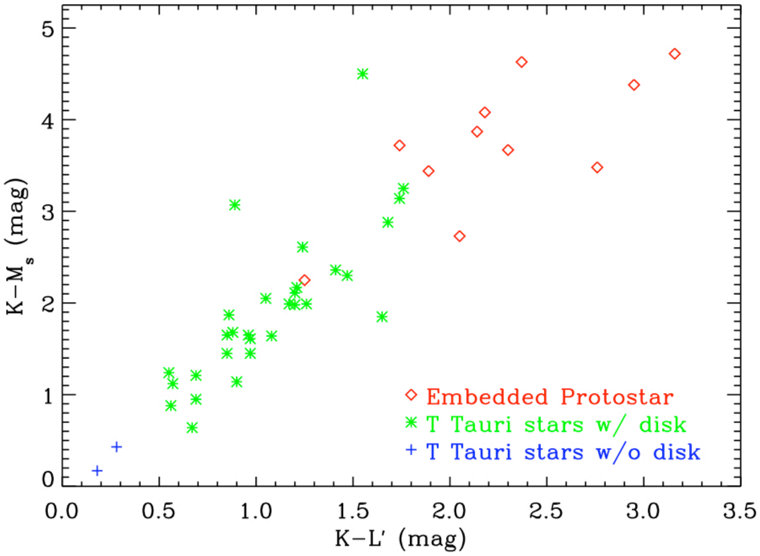

Figure 1 – Near-infrared color-color diagram for embedded protostars and T Tauri stars.

5.1 Stellar colors and variability

In the T Tau system, component N is known to be steady at infrared wavelength, with magnitudes of 5.52, 4.32 and 2.95 at K_{cont}, L' and M_s, respectively (a typical uncertainty of ±0.05 mag should be assigned to these values). Use the flux ratios from the December 2002 observations to determine the magnitudes of T Tau Sa and Sb at these wavelengths, using the following equation:

$$m_1 - m_2 = 2.5 * \log (f_2 / f_1) ,$$

where m_1 and f_1 are the magnitude and flux of component 1. Place all three components in Figure 1, which shows the location of a number of known embedded protostars and T Tauri stars in the Taurus star-forming region. What can you conclude regarding the nature of the components of the T Tau system?

Using the flux ratios you have measured in all datasets, and assuming that T Tau N does not vary at a measurable rate, produce plots of the brightness of T Tau Sa and T Tau Sb as a function of time in the *K* band (around 2.2 μm). Considering the uncertainties, are either (or both) of the two components variable? What could be the source of these variations?

5.2 Orbital motions in the triple system

In the December 2002 images, what is the projected separation of the T Tau Sa–Sb (in arcsec) pair? Of the T Tau N-Sa pair? Convert these separations in a physical distance using the following equation:

$$a = \varrho * D ,$$

where a is the physical separation in AU, ϱ the separation in arcsec, and D the distance to the system in pc.

To determine the orbital period of each pair, use Kepler's third law, which can be conveniently expressed as

$$P = \sqrt{(a^3 / M_{tot})} ,$$

where P is the orbital period in years and M_{tot} the total mass of the system in units of $M_\odot$. For this calculations, assume that the total mass of the T Tau Sa-Sb pair is about 3.3 $M_\odot$ (Duchene et al. 2006) and that of T Tau N is about 2.1 $M_\odot$ (White & Ghez 2001). Can we hope to see significant orbital motion within the system over the course of the 7 yr separating our earliest and latest dataset? Here, we have assumed that the observed projected separation is pretty much equal to the actual separation (i.e.,the vector joining two components of a given pair is exactly perpendicular to our line of sight). If this is not true, in what sense does the predicted orbital period vary?

Generate a plot of the position of T Tau Sb with respect to T Tau Sa as a function of time. Taking into account the uncertainties, is there significant orbital motion? If so, what is the average relative velocity between the two stars in km/s? Remember that you can convert angular distances into physical distance with the knowledge of the distance to the system. In the case of circular orbit, the orbital velocity can be estimated through the following equation:

$$v = 30 * \sqrt{(M_{tot} / a)} \ \ km/s$$

where M_{tot} and a are expressed in units of $M_\odot$ and in AU, respectively. Compare this estimate to your own measurement. Discuss possible discrepancies.

Using the routine provided in Appendix 7, which uses the orbital parameters determined by Duchene et al. (2006), you can compute the predicted position of T Tau Sb relative to T Tau Sa. Compare to the measurements you have made. Was the prediction made by these authors accurate?

Plot the position of T Tau Sa and T Tau Sb with respect to T Tau N as a function of time. Because the T Tau triple system is hierarchical (it contains a tight pair, T Tau S, and a much more distance third component, T Tau N), the motion of these two stars can be described as the combination of the internal orbital motion of T Tau S and the global motion of T Tau S relative to T Tau N. In first approximation, the latter can be approximated by a constant linear motion, given the very long orbital period of the T Tau S-N pair. In practice, it is the barycenter (or center of mass) of the T Tau S tight pair that follows this constant linear motion. Estimate the ratio of the masses of T Tau Sa and Sb that best fulfills this requirement. Which of the two components is more massive than the other one? What is the corresponding linear velocity associated to the T Tau S-N pair, and how does it compare to the prediction based on the observed separation of that pair?

6 Appendix: Computing a theoretical PSF

To compute the theoretical PSF from an assumed entrance pupil (primary mirror), yu can use the following program.

```
pro diffrac,rin,rout,pxscl,fov,wvl

; This program generates a theoretical PSF by computing the Fourier
; Tranform of an entrance pupil. The pupil is assumed to be a filled
; circular aperture (radius rout) with an inner circular opening
; (radius rin).

; rin: inner radius of primary mirror  (in m)
; rout: outer radius of primary mirror  (in m)
; pxscl: desired pixel scale for the generated PSF  (in arcsec/pixel)
; fov: desired field-of-view for the generated PSF  (in arcsec)
; wvl: wavelength at which to compute the theoretical PSF  (in m)

npx=fov/pxscl  ; Number of pixels across the image
pxscl_fft=3600.*180./(fov*2.)*wvl ; Pixel scale for the FT of the pupil (in
m)

pupil=fltarr(npx,npx)

dist_circle,dist,[npx,npx],[npx/2,npx/2]
dist=dist*pxscl_fft

pupil(where((dist ge rin)and(dist le rout)))=1.  ; Pupil=1 within the primary
mirror

tvscl,pupil
stop

otf=fft(pupil)  ; Compute the FFT of the pupil
otf=shift(otf,npx/2,npx/2)  ; Shift it so that the zero-frequency point is in
the center of the image

tvscl,abs(otf)  ; Display the theoretical PSF
writefits,'psf.fits',abs(otf)  ; Save the theoretical PSF as a FITS file

end
```

7 Appendix: Computing the orbit of a binary star based on its orbital elements

The orbit of binary stars are determined by a set of 7 “orbital parameters” that are defined in the PDF file available on the lab webpage. Below is a routine that computes the position of T Tau Sb relative to T Tau Sa based on the orbital parameters determined by Duchene et al. (2006). You can use it to compute the predicted separation of the binary at the epochs corresponding to your datasets.

```
pro orbit,time

; Computes the project orbit of a binary system based on its orbital
; elements. Further estimate the projected separation of the binary at
; a given date, given by "time", expressed as a Julian Date.
; NB: this calculation is valid for times that are less than 1 orbital
; period after the reference periastron passage.

nfit = 2500               ; Number of points to compute over one orbits

Per = 21.66 * 365.25   ; Orbital period [days]
exc = 0.466                 ; Eccentricity
inc = 37.2                    ; Orbit inclination [deg]
big_om = 115.2       ; Position angle of ascending node [deg]
small_om = 12.5         ; Argument of periastron [deg]
Tzero = 2450031.    ; Julian Date at periastron passage
sma = 0.0821               ; Angular semi-major axis [arcsec]

; Modifying Omega and omega to match the subseqeuent equations
big_om=big_om-90.
small_om=small_om-180.

; converting all angles from degrees to radians
inc = inc * !pi / 180.
big_om = big_om * !pi / 180.
small_om = small_om * !pi /180.

; Frequency of the orbit
freq = 2. *!pi / Per
; Useful variable for later calculation
exc_sq = sqrt(1. - exc^2)
; Calculation of the Thiele-Innes elements
TI_a = cos(small_om) * cos(big_om) - sin(small_om) * sin(big_om) * cos(inc)
TI_b = cos(small_om) * sin(big_om) + sin(small_om) * cos(big_om) * cos(inc)
TI_f = -1. * sin(small_om) * cos(big_om) - cos(small_om) * sin(big_om) *
cos(inc)
TI_g = -1. * sin(small_om) * sin(big_om) + cos(small_om) * cos(big_om) *
cos(inc)

; Populting arrays of time and (X,Y) positions from the orbital elements
tfit = fltarr(nfit)
xfit = fltarr(nfit)
yfit = fltarr(nfit)

for i=0,nfit -1 do begin
   u = 2 * !pi * i / (nfit -1)    ;  Angular phase since periastron (at Tzero)
   tfit(i) = Tzero + (u - exc * sin(u)) / freq
```

```
   xfit(i) = -1. * (TI_a * (cos(u) - exc) * sma + TI_f * sma * exc_sq *
sin(u))
   yfit(i) = TI_b * (cos(u) - exc) * sma + TI_g * sma * exc_sq * sin(u)
endfor

; Generating the plot of the orbit
plot,xfit,yfit,xrange=[0.07,-0.13],yrange=[-0.05,0.10],xstyle=1,ystyle=1,$
     /isotropic,xtitle='!7Da!6 (arcsec)',ytitle='!7Dd!6
(arcsec)',thick=3,xthick=3,$
     ythick=3,charthick=3.,charsize=1.25
; Overplotting the periastron
oplot,[xfit(0)],[yfit(0)],psym=4,thick=3,symsize=1.5

; Estimate projected separaion of the binary at date "time"
xtime = interpol (xfit, tfit, time)
ytime = interpol (yfit, tfit, time)

; Projected separation in 2 dimension
rhotime = sqrt(xtime^2 + ytime^2)

; Position angle (North = 0 deg; East = 90 deg)
patime = atan(xtime / ytime) * 180. / !pi
; Correcting the PA to match the astronomical convention (0 - 360 deg)
if xtime lt 0. then begin
   patime = patime + 360.
endif

print,'Offset along R.A. axis (positive toward E) : ',xtime
print,'Offset along Dec. axis (positive toward E) : ',ytime

end
```

8 References

Duchene et al. 2006, Astronomy & Astrophysics Letters, 457, L9
Loinard et al. 2007, The Astrophysical Journal, 671, 546
White & Ghez 2001, The Astrophysical Journal, 556, 265