An Orion BN/KL Twin - The Interstellar Bullet Engine IRAS 05506+2414

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Introduction

High-mass (>8 Msun) stars play a decisive role in the evolution of galaxies.

Throughout their life-cycles, they inject large amounts of energy and momentum into their environments through massive stellar winds, UV radiation, and finally in their deaths as supernovae.

In their earliest stages, massive stars and their immediate environments are characterized by

high luminosities (> ~10^4 Lsun)

dense and warm molecular gas

strong far-infrared dust emission

very weak or no free-free continuum emission

Like their low-mass counterparts, high-mass protostars also exhibit bipolar outflows with varying degrees of collimation and outflow luminosities (e.g., Qiu et al. 2008**)**

<u>Explosive Outflows from Massive Stars</u>

An exciting result related to this early evolutionary stage:
<u>Wide-angle outflow</u> from BN/KL region: produced by a violent explosion during the disruption of a massive young stellar system ~500 yr ago
(based on CO J=2-1 interferometric mapping of the outflow [Zapata et al. 2009], proper motion study of H_2 "fingers" [e.g., Bally et al. 2011]).

Bally et al. (2011) provide detailed models for this outflow being powered by the dynamical decay of a multiple system that ejected two massive stars and a compact binary (I, BN and source n)

This is an entirely different phenomenon from the classical bipolar flows driven by YSO accretion disks: ***is the Orion BN/KL outflow and its engine unique, or simply an example of a rare phenomenon?***

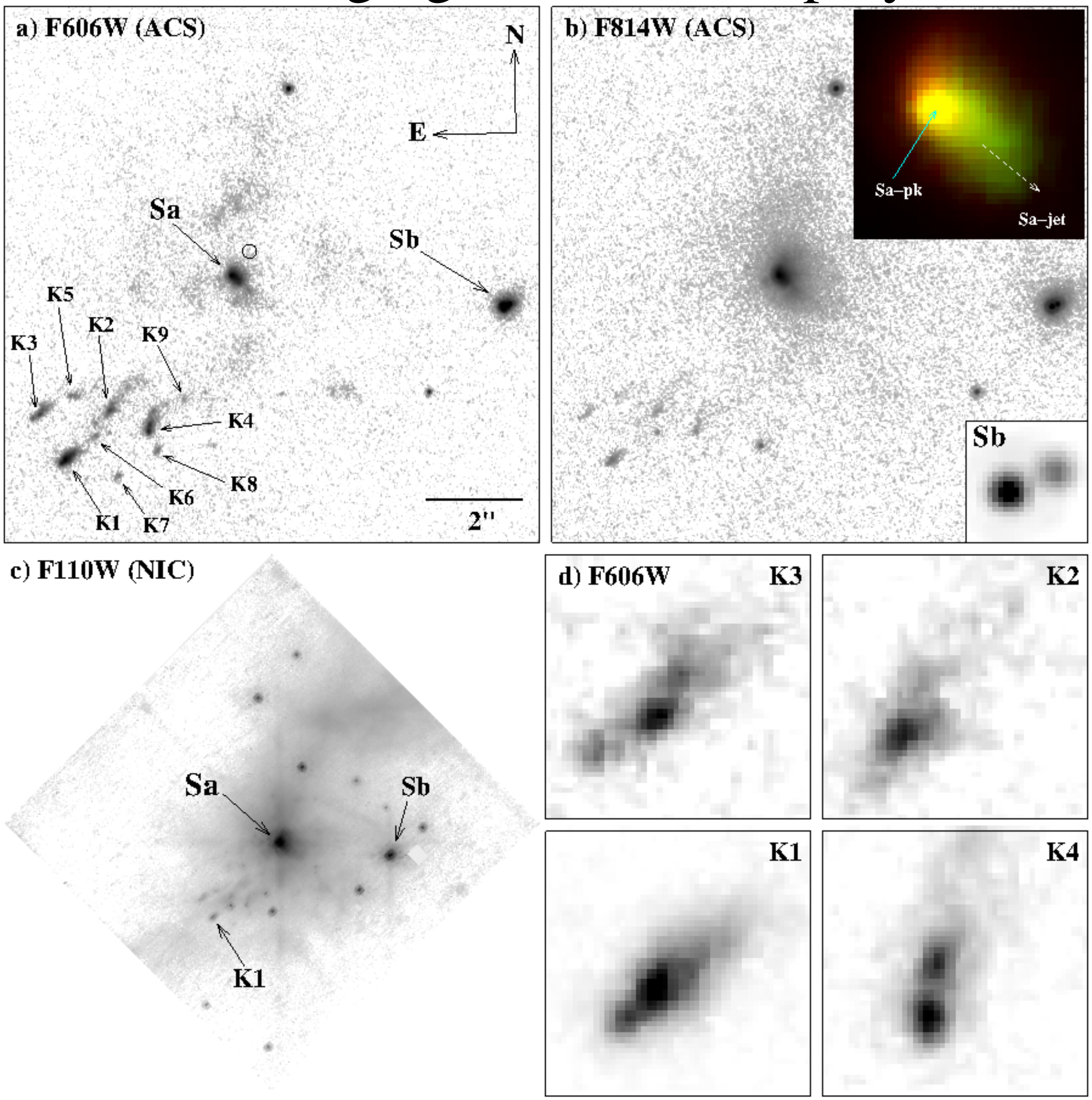
A New Interstellar Bullet Source IRAS05506+2414

***IRAS 05506+2414 (serendipitous discovery in an HST survey of pre-planetary nebulae) appears to be the second clear-cut example of this phenomenon* in our Galaxy (**Sahai et al. 2008 [Setal08]**).**

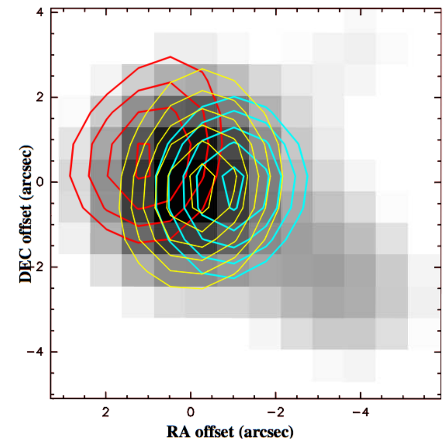
Bally et al. (2011) suggest additional examples as well (e.g., G34.25+0.16, NGC7129, Source G/W49), but **none of these appear as similar to Orion BN/KL as IRAS05506**

Our HST optical and near-IR images show a fan-like spray of high-velocity (up to 350 km/s) elongated knots that appear to emanate from a bright compact central source (Sa) with a jet-like extension (Sa-jet).

HST imaging: The Bullet Spray



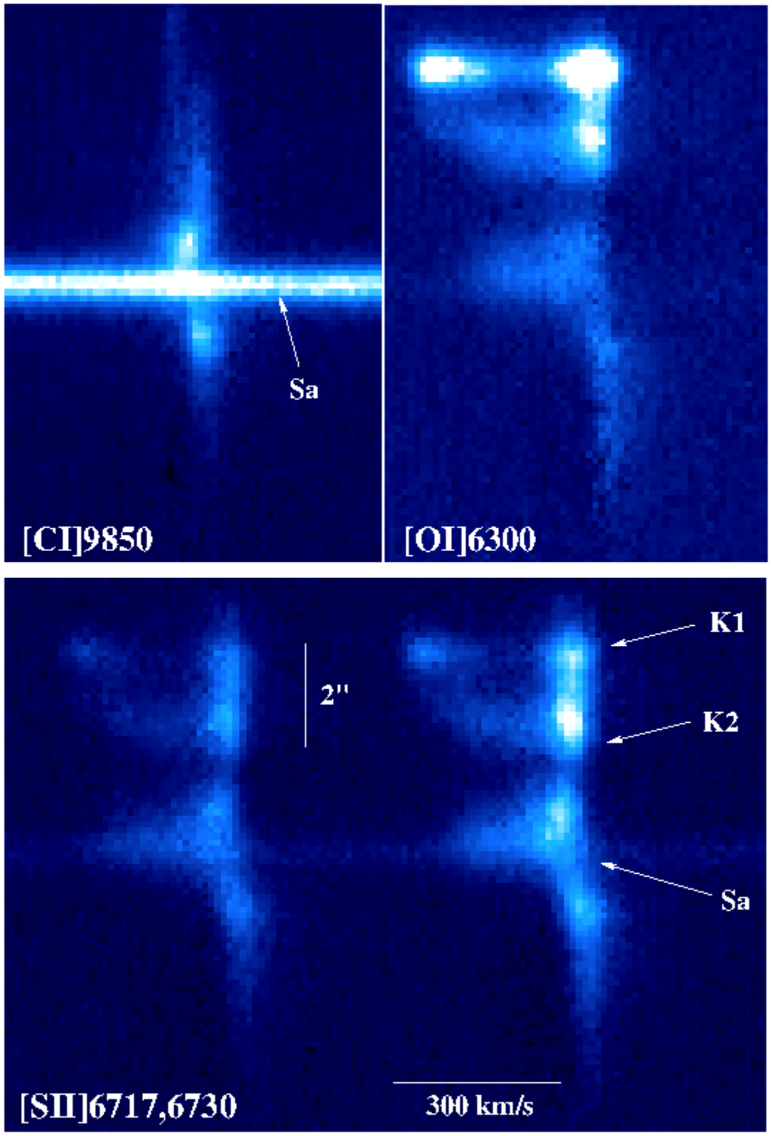
OVRO CO 1-0 Secondary Outflow



HST maging:
HST/ACS (*panels a,b,d*) and NICMOS (*panel c*)

Expanded views of
(i) the interstellar bullet source Sa (and possible binary Sb) (*panel b*)
(ii) bullets (*panel d*). circle in *panel a* marks location of water maser.

Keck-ESI Optical Spectroscopy



Slit aligned along line joining Sa & K1,K2

(spectrum covers 3900-10900 A, but virtually no signal shortward of ~5500 A)

spectral type uncertain:
estimate late-G to early-K; metallic absorption lines present, Paschen lines absent (Setal08)

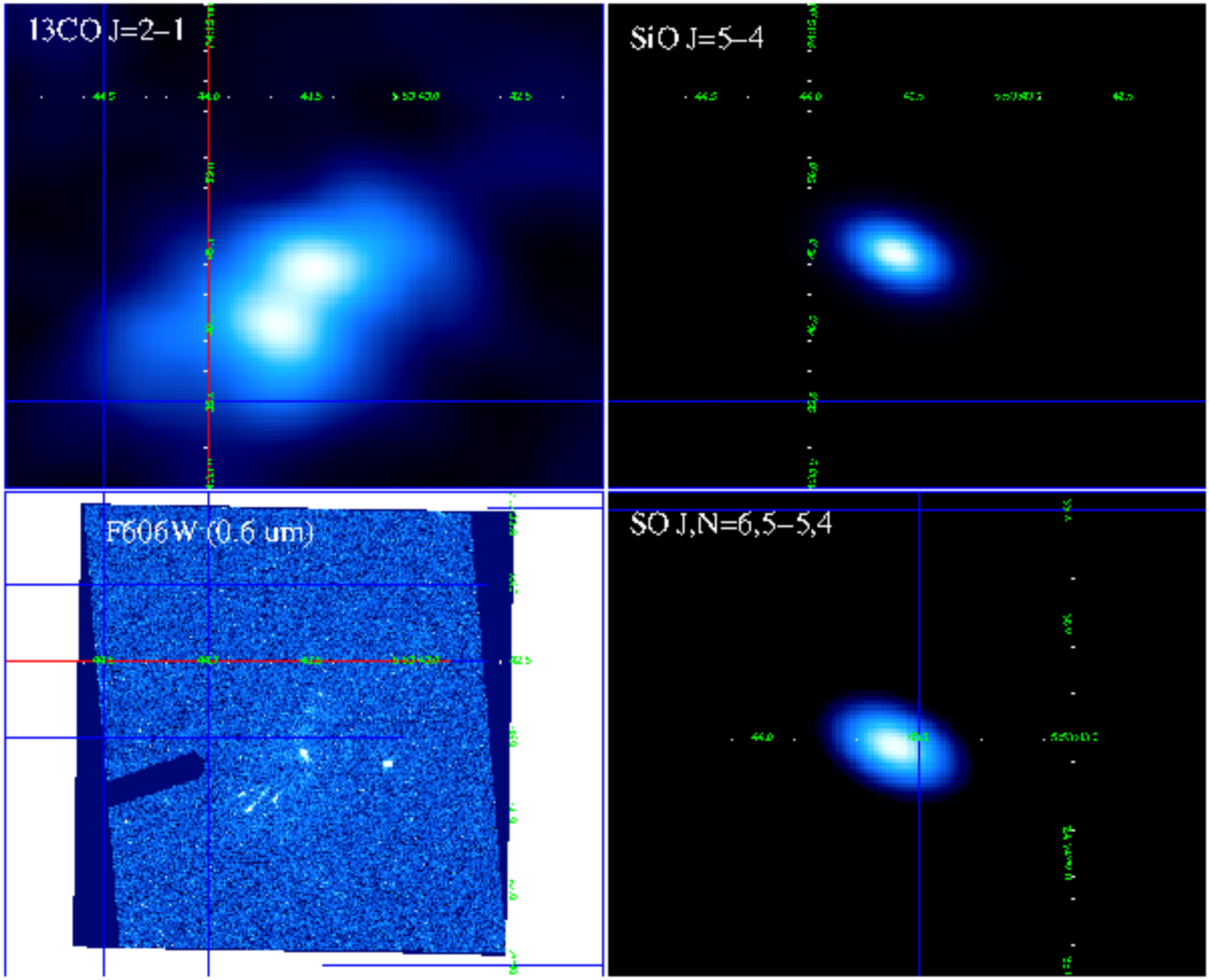
(1) Knots show Hα and forbidden emission-lines similar to Herbig-Haro objects and a P-V signature characteristic of bow-shocks

(2) Red-shifted emission likely due to emission from a central source being scattered by a dusty outflow.

(3) The [CI] emission has a different spatial distribution than other nebular lines such as [SII] and [OI] - it peaks on and near Sa, and is not seen in the knots.

I(λ9824+λ9850)/ **I**(λ8727) can be used to test emission mechanism: (a) radiative recombination of C+ ions produced in high-density PDR (as in M42: Escalante et al. 1991), or (b) collisional excitation (as in NGC7027: Jewitt et al. 1983)

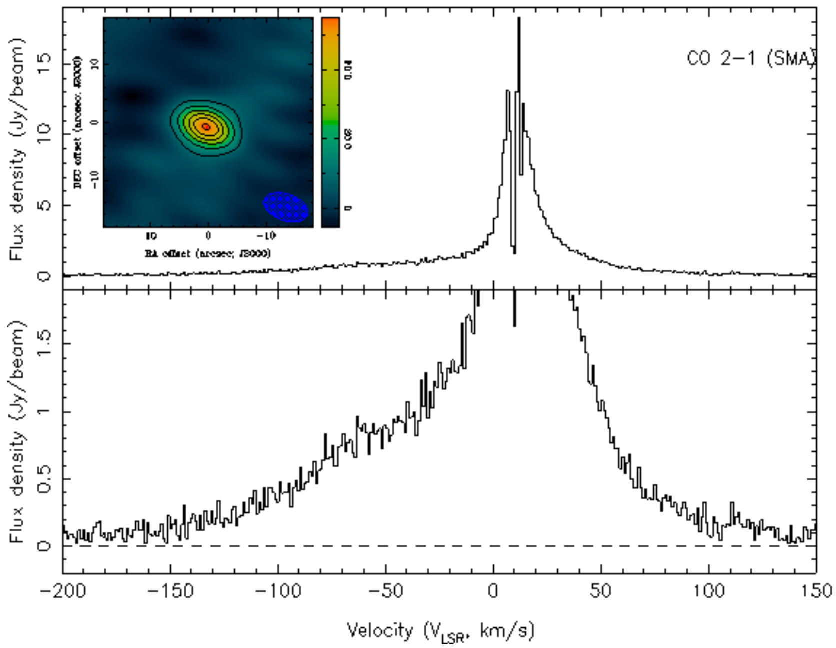
SMA maps (subcompact array)

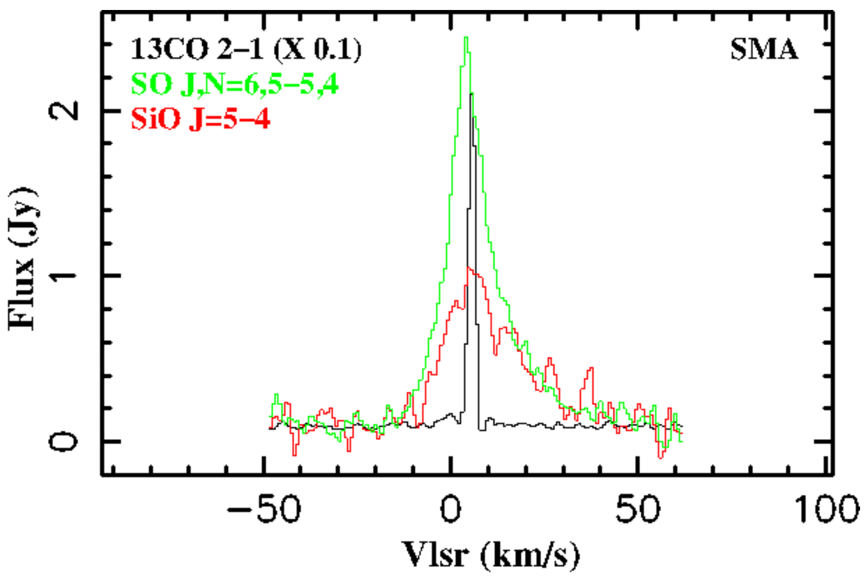


1.3 mm imaging: ~2 hr "filler" track with array in subcompact configuration (beam ~7" x 3"):

- **The ^{13}CO J=2-1 map shows two peaks, one located at Sa, and the other in the region of the wide-angle spray** (low-velocity emission)
- **The SiO and SO** (high-velocity) **emission is located at Sa and is unresolved.**

SMA: Line profiles





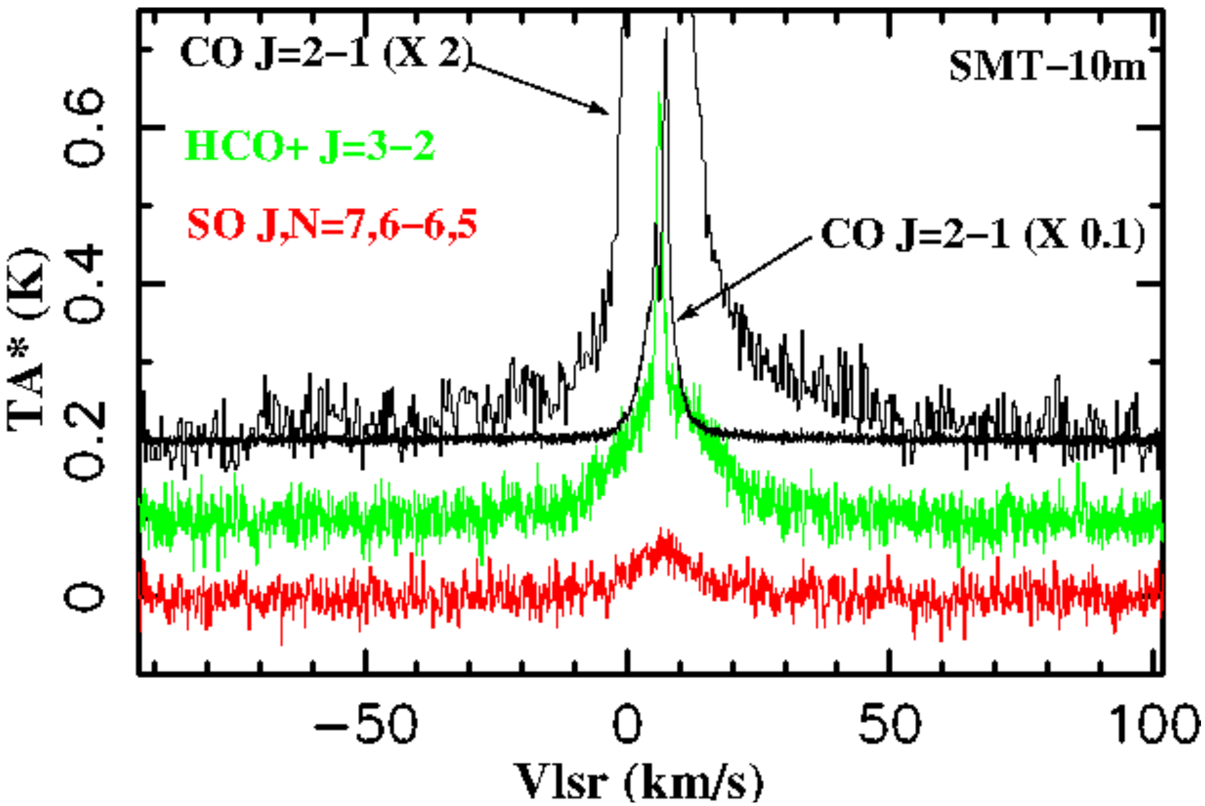
- **Strong CO J=2-1 emission with very wide wings (+/- 150 km/s) (**inset shows 67 mJy continuum source**)**

- **The SiO and SO lines show a triangular profile, with FWZI of ~45 km/s. In contrast the ^{13}CO line shows only a narrow component.**

OVRO interferometric observations of CO J=1-0 (with 3.9" x 2.9" beam) also show high-velocity wings and continuum source (unresolved)

Single-dish Spectra

(Kitt Peak 12m, SMT 10m: 60”-30” beam)



High-density, shock tracers:
Multiple molecular lines detected

- **HCO^+ J=1-0, 3-2**
- **SO (J,N=4,3-3,2; 3,4-2,3; 5,6-4,5; 7,6-6,5)**
- **CS J=2-1**
- **H_2CO 2(1,1)-1(1,0)**

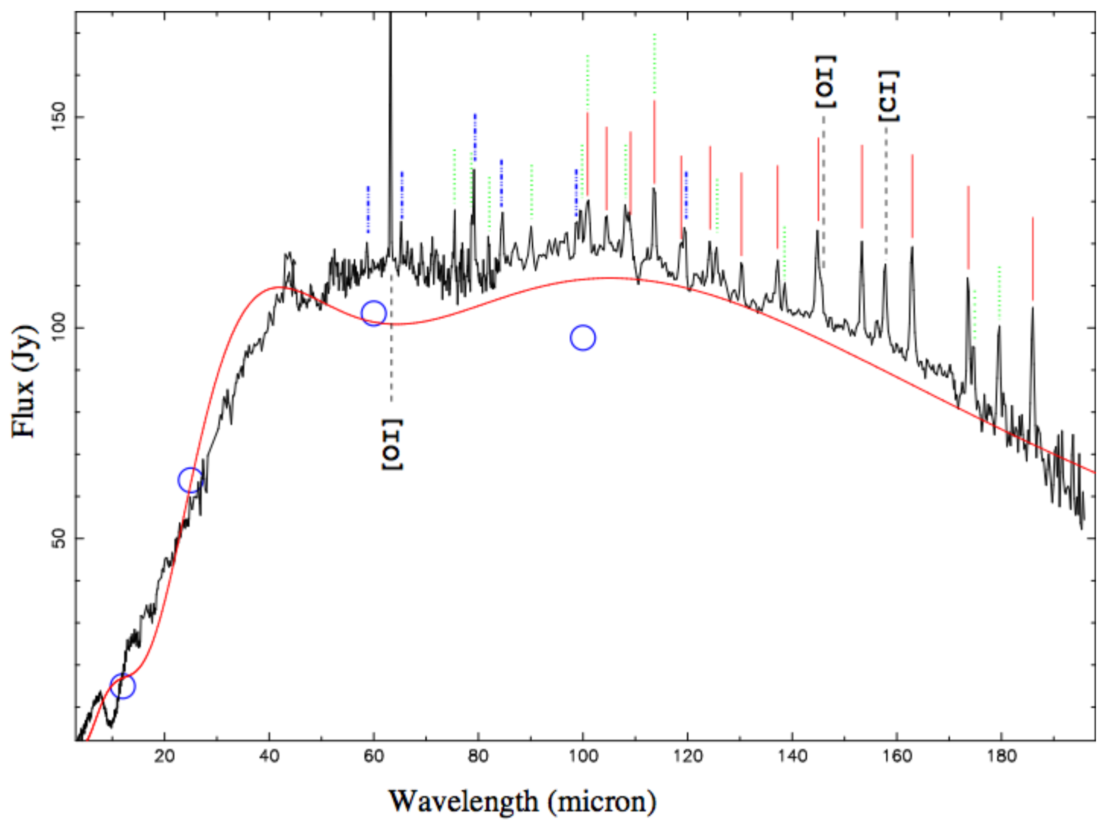
(upper limits on SO2 lines)

HCO+ and SO lines show a triangular shape with FWZI of ~30 km/s

On-source high S/N line profiles of CO, ^{13}CO, and $C^{18}O$ (J=2-1, and/or 1-0): CO shows high-velocity wings and a self-absorbed narrow core.

Map of extended molecular cloud in CO J=1-0 shows extended cloud, size > 30’ X 12’

ISO SWS/LWS spectrum



CO lines from J=14-13 to J=26-25 shown by vertical red bars, and those of the most prominent lines of H_2O (ortho- and para-) and OH are marked by green and blue vertical bars. Red curve is simple thermal emission dust model

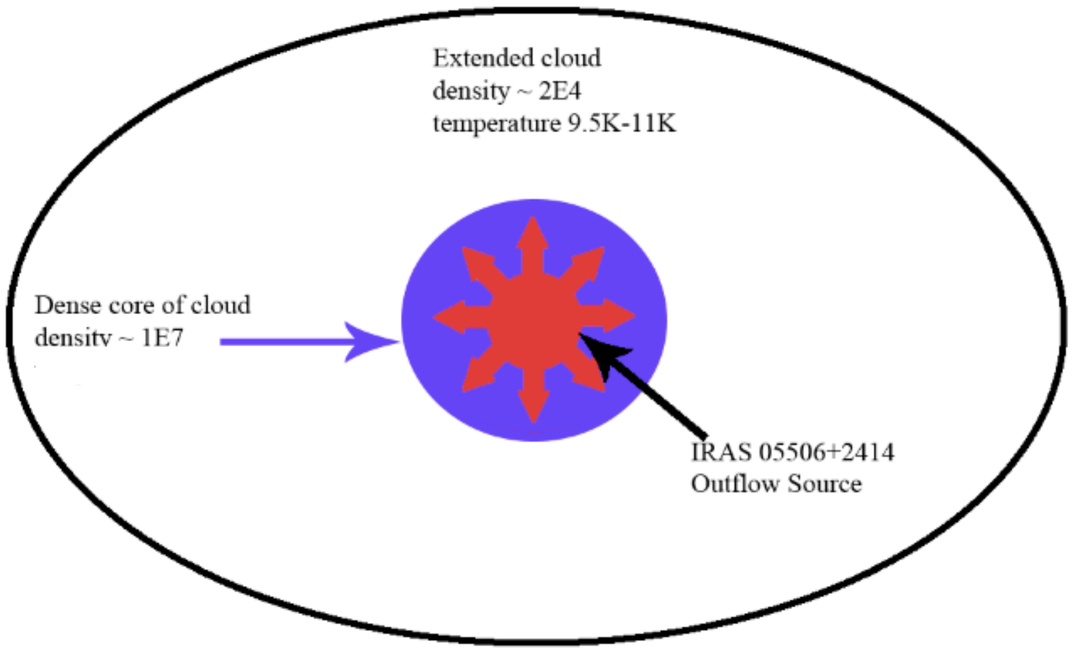
Fit SED using the online least-squares fitting of pre-computed disk-envelope models of YSOs (Robitaille et al. 2007)

for an input distance range of 0.1-5 kpc, the top 3 best-fit models:

distance D = 2.2, 2.6, 3.0 kpc (L=3150-5850 Lsun)

central star mass M = 8.5, 10.6, 11.2 Msun

central star Teff= 4190, 4430, 4280 K



A Toy Model of the Sa Outflow Source and Environment

- **Central Outflow Source**

(< ~5 arcsec size)

high-density outflow with Vexp~15 km/s (HCO+, SO, SiO triangular line profiles)

lower density outflow with Vexp~50-100 km/s (CO line wings)

- **High Density Core**

Hot (T~500-800K), *dense* (n~ upto 10^7 cm^{-3})

ISO LWS spectra: high-J CO lines (J=14-13 to 32-31)

[OI]63μm/146μm vs [OI]63μm/[CII]158μm (Liu et al. 2001)

- **Medium Density Cloud** (1 arcmin size)

(NH3 map/ far-IR thermal dust emission: 10-25 Msun)

- **Ambient cloud** (~10 K, produces self-absorption in ^{12}CO lines), M ~ several 100 Msun)

SUMMARY (1)

- **IRAS05506 is a young object**

presence of OH maser emission suggests that it is not a low-mass YSO, as there are no known OH masers toward low-mass YSOs.

- **No measurable radio continuum (<50 μJy at 8 GHz)**

(i) the central HII region is very small and the radio continuum is below our noise limit, or

(ii) the central star has been caught at a very early age while its temperature is still too low to provide sufficient ionizing UV flux, consistent with the central star's late spectral type (late G - early K)

- **Molecular-line data show a dense, dusty cloud associated with IRAS05506 embedded in a larger lower-density molecular cloud.**

Summary (2)

Bullet spray characterized by high-velocities (up to 350 km/s)

Elongated knots appear to emanate from a bright compact central source (Sa) with a jet-like extension (Sa-jet)

Many physical properties of the IRAS05506 outflow source appear very similar to the one in Orion (e.g., Nissen et al. 2007**)**
(although TOTAL energetics and ejected mass significantly smaller)

<u>Primary Wide-Angle Outflow</u>

IRAS05506 (Orion BN/KL**)**

Opening Angle: >45 deg (75 deg**)**

Knot masses: (e.g., knot K1) **2 x 10^{-5} Msun (**~ 10^{-5} Msun**)**

Radial extent: ~ (1.5-2) x 10^{17} cm (~ 2 x 10^{17} cm**)**

Kinematic Age: 200 yr (< ~ 600 yr**)**

Secondary Outflow with axis roughly orthogonal to wide-angle spray (NE-SW outflow seen, e.g., in SiO)

Summary (3)

Most physical properties depend on D or D^2, and have been derived for D=2.8 kpc

Secondary outflow (using CO J=1-0 line OVRO interferometric data)

mass (D^2) > 0.2 Msun

mass-outflow rate (D) > 9.7 10^{-4} Msun/yr

scalar momentum (D^2) > 4.3 Msun km/s

mechanical energy (D^2) > 4.6 10^{45} erg

mechanical power (D) > 7.9 10^{35} erg/s

Luminosity of Sa (D^2) **~5000 Lsun**

At the current (very uncertain) distance of 2.8 kpc, the luminosity is consistent with Sa being a massive star (9-15 Msun)

Masses of knots, kinematic age, mass of dense molecular core and extended cloud all depend on distance

Hence, determination of distance to source is a very important step in understanding IRAS05506 and its outflows.

CURRENT & FUTURE WORK

1) HST: proposed 2nd-epoch observations to determine proper motions of knots and infer the "expansion parallax" distance to the source and thus its fundamental physical properties

2) SMA: 1" resolution mapping at 1.3 mm of molecular lines/continuum ((1-track in extended-configuration: Feb2012)**)**

Analysis of these data will enable us to determine the structure and collimation of the secondary high-velocity outflow, and probe its association with the optical Sa-jet feature.

3) Construct quantitative physical model of source

4) NIR spectroscopy: spectral typing and search for radial-velocity variations - evidence for binarity

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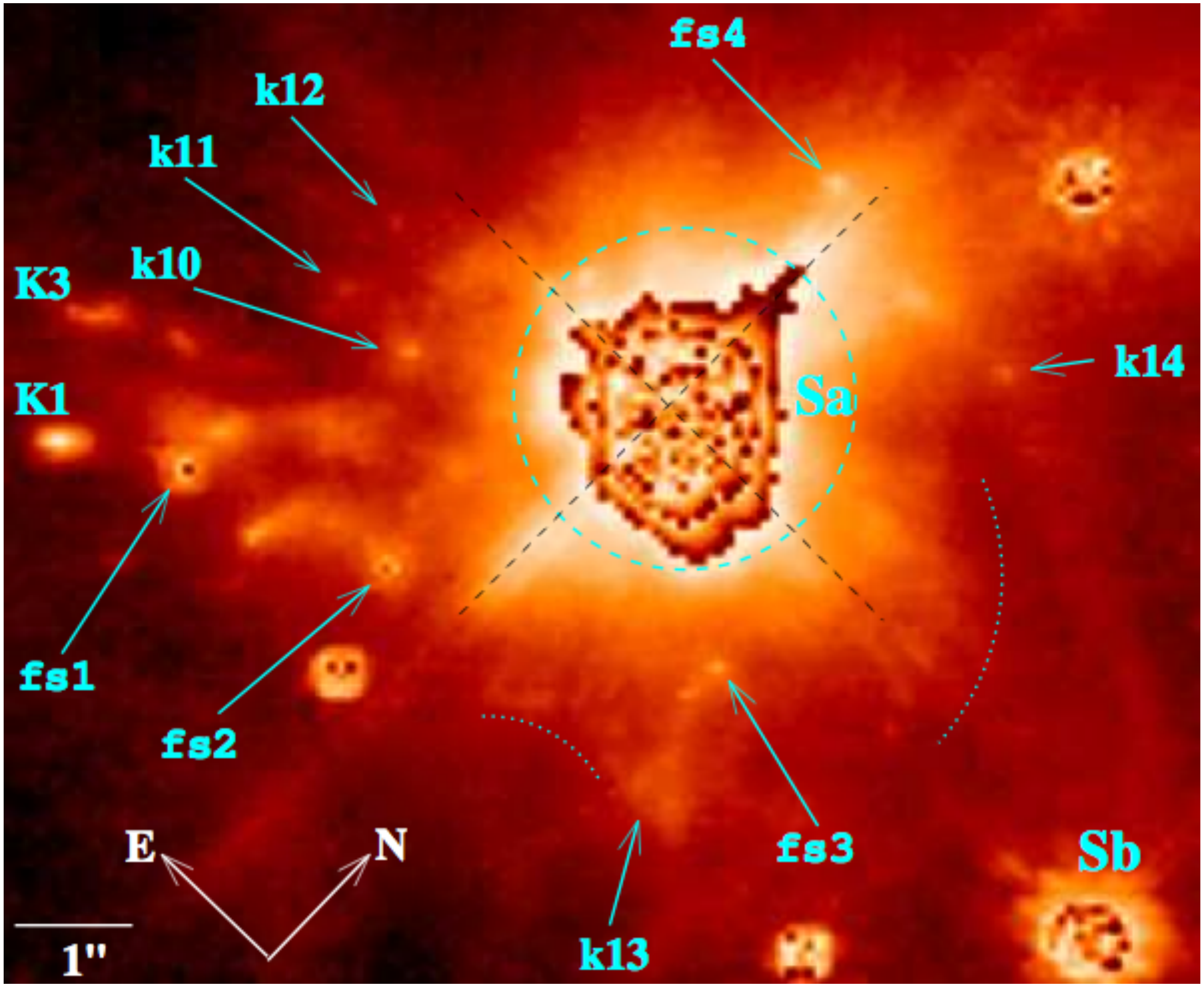
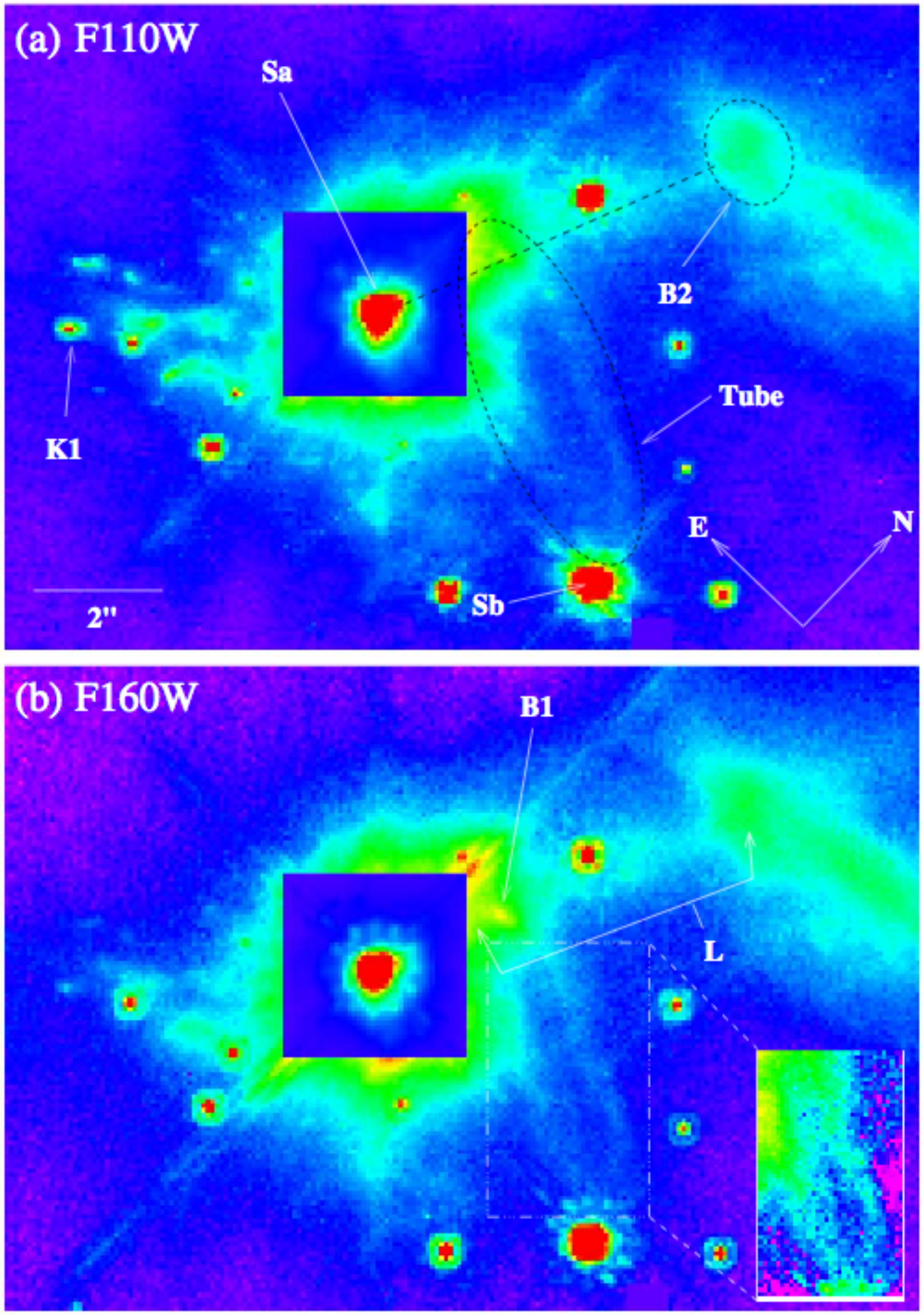
HST/NICMOS image



NICMOS 0.11 µm image highlighting the presence of knotty structures k10-k14 not seen in the F606W ACS image (some of the common features (K1, K2, Sa, and Sb are also labelled for visual registration).

The greyscale shows log(log (I)), where I is the intensity

Faint stars in this image are labelled fs1-fs4. The dashed circle covers a central region around Sa where knotty structures cannot be reliably distinguished from PSF structures.



- NICMOS images F110W and (b) F160W NICMOS images highlighting the presence of low-contrast features.

- The intensity in the very bright central region surrounding Sa has been scaled down by a factor 0.06 (0.03) in the F110W (F160W) image

- The large ellipse (panel a) encircles a tube-like structure; inset in panel b (lower right corner) covers a 2.5'' x 4.3" patch around the Tube with a different stretch to show its faint parts more prominently

- The dashed straight line (panel a) marks a roughly linear structure joining two locally bright regions B1 and B2.