October 2008

Challenges in Radiative Transfer Modeling - W3 IRS5

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Working with Murray F. Campbell and Ryland T. Brooks - Spring 2006

Motivation

By modeling the spectral energy distribution (SED) of the W3 IRS5 high-mass star formation region and matching this model to observed data, we can constrain the physical parameters of the basic system geometry and cloud mass distribution. From these parameters, we hope to add to the understanding of high-mass star formation processes. In particular, we hope to determine if the geometries associated with low-mass star formation carry over into the high-mass regime.

Background

The subject of high-mass star formation is a topic of great interest and debate with many questions yet to be answered. Factors that contribute to the slow progress in the field include the rapid timescale for high-mass star evolution, which leads to a relatively small number of high-mass stars available for study and therefore a greater average distance to each. Also, protostars are always embedded in clouds of gas and dust, eliminating the possibility of study using the visual portion of the spectrum, leaving the infrared as the best possible means of studying these systems.

There are two leading theories explaining high-mass star formation. The first is that of coalescence, where high-mass stars are formed through stellar mergers occurring in high-density clusters. The second and more commonly accepted theory is that of accretion-based formation. As in the well-established theory of low-mass star formation, mass accretes onto the star from the surrounding envelope of gas and dust, creating both a thick circumstellar disk of dust and bipolar jets of ejected stellar material. These elements are depicted in the figure below.

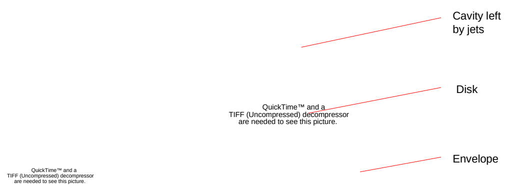

FIG 1. - A Hubble Space Telescope image of HH30 showing a genuine disk and jet system. Also, a simple diagram of the geometry expected from a protostellar system according to the theory of accretion-based formation.

The object of interest for our analysis is the W3 IRS5 high-mass star formation region. W3 IRS5 is the next closest region of high-mass star formation after the Orion Nebula, at a distance of 1.83 $\pm$ 0.14 kpc (Imai et al. 2000). This region has been thoroughly studied due to its proximity and because of its brightness, with a luminosity of 1.45×10^5 Lsun at 1.83 kpc (Campbell et al. 1995). Professor Campbell and collaborators conducted observations of this region utilizing both the Kuiper Airborne Observatory (KAO) in 1987 and 1989 (Campbell et al. 1995) and the Infrared Telescope Facility (IRTF) atop Mauna Kea in 2002 (see poster by R. Brooks).

References

Campbell, M.F., et al. 1995, ApJ, 454, 831
Howell, R.R., et al. 1981, ApJ, 251, L21
Imai, H., et al. 2000, ApJ, 538, 751
Indebetouw, R., et al. 2006, ApJ, 636, 362
Megeath, S.T., et al. 2005, ApJ, 622, L141
Neugebauer, G., et al. 1982, AJ, 87, 395
van der Tak, F.F.S., et al. 2005, A&A, 431, 993
Whitney, B.A., et al. 2003, ApJ, 591, 1049

Acknowledgements

I would like to thank Murray Campbell for all his help and guidance throughout this project. I would also like to thank Ryland Brooks for his partnership on the project and Dr. John Kuehne for his computer support at Colby College.

Analysis and Results

Our analysis consists of modeling the spectral energy distribution (SED) produced by the W3 IRS5 system. An SED is a plot of luminous flux (energy) as a function of wavelength. This energy is in the units of Janskys (Jy), where 1 Jy equals 10^{-26} $Wm^{-2}Hz^{-1}$. In this investigation we are only concerned with the infrared-submillimeter spectrum, ranging from approximately 1 to 1000 microns (μm).

Using a 2-D Monte Carlo modeling code developed by Barbara Whitney (Whitney et al. 2003), we modeled our source as a star with a circumstellar disk and bipolar cavity enclosed within an overlying envelope. This technique is an improvement over past methods of 1-D spherically symmetric modeling, where adding disk or cavity components was not possible.

Models were fit to data collected by Professor Campbell and collaborators on the KAO and at the IRTF, in addition to photometric data found in current astronomical literature (Campbell et al. 1995). We present here the best-fit model to date in an ongoing modeling effort. System parameters used for this model are listed in Table I. In the process of fitting the model, the angle of the cavity opening had a great effect on the shape of the resulting SED, while disk parameters (mass and radius) were not strong constraints. The best-fit SED given here is not only a function of the input parameters, but also a function of viewing angle of the observer. Due to the non-uniformity of the system geometry, different viewing angles yield different SEDs, as represented by the different colored plots, each representing a specific angle.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

TABLE I.

Model Parameters

Parameter	Value
Stellar radius (Rsun)	10.06
Stellar temperature (K)	35500
Stellar luminosity (Lsun)	1.45E+05
Stellar mass (Msun)	60
Disk mass (Msun)	10
Disk inner radius (AU)	31.5
Disk outer radius (AU)	2000
Disk density exponent	-2.25
Envelope mass (Msun)	850
Envelope inner radius (AU)	12600
Envelope outer radius (AU)	55600
Envelope density exponent	-1
Cavity opening angle (degrees)	35
Cavity density exponent	-2

FIG 2. - The SED of our best-fit 2-D radiative transfer model. Parameters for this model are given in Table I. The viewing angles range from pole-on (pink) to edge-on (green).

Modeling Challenges

While 2-D modeling is an improvement on past 1-D modeling efforts, even this method has its limitations. If a "clumpy" model of the surrounding circumstellar envelope is utilized, where gas and dust randomly forms high-density clumps within the cloud, a 3-D modeling procedure is needed to characterize such geometries. These clumps add another element of viewing angle dependency, which make definitive modeling effectively impossible. This is due to the fact that subject to clump location, nearly any SED can be created from a single set of physical parameters, as depicted in the figure below. The only solution to the possibility of clumpy circumstellar envelopes is to obtain very high-resolution images of a source to determine the distribution of clumps, which could be possible through the use of very large aperture telescopes.

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

FIG 3. - The images at top-left are computer generated images of a source embedded within a clumpy dust distribution. Image A (upper) is taken from the perspective of viewing angle A, and image B (lower) is taken from the perspective of viewing angle B. These two viewing angles are shown in an azimuthal slice of the system's density distribution in the image at top-right. To show the differences in the observations made of the same source at these two different viewing angles, the SEDs as seen from A and B are plotted in the graph at bottom (Indebetouw et al. 2006).

W3 IRS5 Complexities

Though the 2-D Monte Carlo code uses a simple single source model, this in fact is not the case for W3 IRS5. Howell et al. (1981) and Neugebauer et al. (1982) resolved the system into a binary infrared source. Furthermore, Megeath et al. (2005) detected three additional infrared sources, opening the possibility that this system is an early trapezium system embedded in its natal gas cloud. This multiplicity of sources creates a modeling nightmare, in which the complexities are too great for any non-specialized modeling code to handle.

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FIG 4. - A high-resolution Hubble Space Telescope image of the W3 IRS5 system which successfully resolves the source into multiple sources. NIR1 and NIR2 make up the original binary resolved by Howell et al. and Neugebauer et al., while NIR3, NIR4, and NIR5 were the sources newly resolved in this 2.22 μm image (Megeath et al. 2005).

We believe that our model still offers valuable if approximate information about the overall system. We approximate the multiple protostars as a single source within a shared outer envelope, which seems reasonable due to their close proximity. In addition, Imai et al. (2000) concludes that outflows from the multiple sources align in a single direction, providing a logical argument for approximating the system as having a composite bipolar outflow cavity. While detailed information about the individual sources is not possible to derive from our models, obtaining general parameters of the overall system is still within the realm of possible modeling outcomes.

FIG 5. - A schematic detailing the complexity of the W3 IRS5 region, with physical components labeled (van der Tak et al. 2005). While this is no longer the simple system we modeled, overall the region can still be characterized in terms of the same basic geometry.

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FIG 6. - A schematic of the spatial relationship between the multiple outflows found in the W3 IRS5 region (Imai et al. 2000). While the outflows are distinctive of one another through careful analysis, their similar alignment allows for the accurate approximation of a single composite outflow.