Gas, Dust and Ice in Bipolar Outflows

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mm workshop 29-30 Nov 2001

Outline

- Bipolar outflows a brief introduction
- Questions to be answered about bipolar outflows
- Optical and infrared studies of gas, dust and ice; what can they tell us?
- mm studies and the role of the ATCA

• Two examples at opposite ends of the evolutionary scale, illustrating how optical, infrared and mm observations can complement each other

A reminder: We have been studying bipolar outflows based mainly on infrared observations of the dust and ice associated with them. This strongly biases our sample.

Bipolar Outflows - an introduction

Molecular outflows are associated with stars in both the early and late stages of their evolution. Generally the outflows have a bipolar morphology. A number of models have been proposed to explain this morphology and the associated kinematics. For example, Lee et al. (2000) describe two models ...

• The jet-driven bow shock model, where a jet propagates into the ambient medium and forms a bow shock at the head of the jet. As it moves away from the star the jet interacts with the ambient material producing the molecular outflow

• The wind-driven-shell model, where the star expels a wide-angle magnetized wind that plows into the ambient medium. The ambient material is swept up by a shock that runs ahead of the wind bubble and produces the molecular outflow.

A typical(?) bipolar outflow ...

From our (infrared) point of view the basic observational characteristics of a bipolar outflow are (i) a central star obscured by a thick circumstellar disc, (ii) a wind-blown bubble which may contain H-H like objects, and (iii) a swept up shell which may also contain H-H like (shocked) knots.



Diagram adapted from Snell et al. (1980)

A few questions about bipolar outflows ...

- What is the composition of the dust in the disk and the outflows?
- How does the dust in the disk and the outflows compare to the diffuse I SM and the ambient medium?
- Are there shocks in the disk and/or the outflows?
- Where are the shocks in the outflows?
- Are these shocks able to modify the dust?
- What molecules are present in the outflows?
- What sort of chemistry is induced by the shocks?
- What is the relationship between the dust and the gas?

What can infrared observations of the dust do for us?

Infrared spectroscopy and imaging over an extended wavelength range, combined with a model to interpret the results, can give us information on the dust, such as ...

- grain material (e.g. Silicates, Hydrocarbons, etc)
- grain size distribution
- indicate the presence of ice mantles
- grain shape
- grain orientation

How do ice observations help?

They can give us clues to ...

- the temperature history of the dust
- physical conditions in the cloud or disk
- chemistry in the cloud or disk



I ce condensation temperatures

<u>Molecule[†]</u>	<u>Temperature</u>
H ₂ O	90K
НСООН	85K
CH ₃ OH	75K
HCN	69K
NH ₃	56K
CO ₂	49K
H ₂ CO	45K
OCS	40K
CH ₄	18K
CO	16K
[†] detected toward W33A (Gibb et al. 2000	

Optical observations probe both the gas and the dust

 optical (and infrared) polarimetry can be used to constrain the size of the dust particles

 optical continuum imaging can be used to examine the spatial distribution of scattered light from the dust

 optical spectroscopy and line imaging can be used to examine the gas kinematics and identify regions affected by shocks

What role can mm observations and the ATCA play?

The upgraded AT Compact Array, operating at 12 and 3 mm will provide the capability for imaging at near arcsecond resolution over an area ~ 30-40 arcsec in diameter (without mosaicing). This capability, along with the substantial number of molecular lines observable at these wavelengths makes the ATCA a major tool for studying bipolar outflows. A few of the possibilities ...

- Outflow structure
- Shock chemistry in the disk and outflows
- Outflow kinematics



Two examples of bipolar outflow sources and the optical, infrared and mm observations of them.

Example 1 is an evolved object well studied at all wavelengths at high spatial resolution. Its size on the sky is such that almost the entire object could be observed within the ATCA beam.

Example 2 is a young object not nearly so well studied. The scale of its outflows is so large that it would probably be impractical to observe in its entirety with the ATCA. However, the outflows close to their point of origin could be studied in much more spatial detail than example 1.

Example 1: OH231.8+4.2 - an evolved star with a bipolar outflow



 $H\alpha$ image from Reipurth (1987)

- Oxygen-rich AGB star (M9 III)
- Mira variable (700 day period)
- high mass-loss rate (10⁻⁴ M_{\odot} /yr)
- OH, H₂O and SiO masers
- obscured central star/extensive disk
- bubble (lobe) walls and axial flow
- HH knots/bow shocks at the ends of the lobes
- northern lobe closest ($\theta \sim 36^\circ$)
- Silicates and H₂O ice in the disk

Polarisation associated with OH231.8+4.2

- the centro-symmetric pattern in the lobes indicates the nebula is seen in reflected light from a central source in the dust lane
- in the dust lane the polarisation pattern is consistent with a disk
- OH231.8+4.2 fits our 'typical' outflow model



from Kastner & Weintraub (1995)

Polarimetry and I R imaging (next slide) let us constrain the dust grain properties in different regions of the object (disk, axial flow, lobe walls, etc.).

Our observations (sub-arcsec IR imaging):



Even higher spatial resolution from a HST image[†] of OH231.8+4.2 reveals structural details of the ...

- Northern knots
- Lobe walls
- Axial flow
- Central source (now visible)
- Lobe walls

What if we now want to probe the gas at similar resolution?

⁺NASA, ESA PR99-39, Bieging et al. 2000



Integrated ¹²CO J=1-0 and J=2-1 emission:

Alcolea et al. 2000 find that ...

 the gas is confined to a very narrow region along the symmetry axis.

• (Kinetic) temperatures range from 8K in the south, to 35K in the centre, to 23K in the northern knots (shocks?). • most of the nebular mass (0.6 M_{\odot}) is in the central condensation, expanding at < 40 km/s.

• the rest of the gas (0.3 $\rm M_{\odot})$ is flowing along the nebular axis at high velocities (< 400 km/s).



from Alcolea et al. 2001, PdB 5 x 15m

OH231.8+4.2 shows rich molecular emission:

At $\lambda = 1.3 \text{ mm}$ ¹²CO(2-1) ¹³CO(2-1) SiO(5-4) CS(5-4) At $\lambda = 2 \text{ mm}$

 $SO_{2}(10-9)$

At $\lambda = 3 \text{ mm}$ ¹²CO(1-0) ¹³CO(1-0) HCO⁺(1-0) HCN(1-0) H¹³CN(1-0) HNC(1-0) SO NS

• The presence of HCN/HNC is interesting in an O-rich environment.

• Except for HCO⁺ the spatial and kinetic extent of these molecules is similar to CO, i.e. a dominant central clump and weaker emission in the lobes.



from Sánchez Contreras et al. 1997

Mapping the molecular emission:

- HCO⁺ does not show the dominant central feature of the other molecules.
- It is enhanced in the lobes, perhaps due to shock induced reactions?
- The variety of N- and Sbearing molecules indicates an active (shock?) chemistry.



In OH231.8+4.2 we seem to be seeing the result of the interaction between recent, fast bipolar jets and the previous AGB envelope. However, the spectral type of the central star is characteristic of an AGB star while the bipolarity and high velocity axial flow are more characteristic of a post-AGB object.

A few questions raised by the observations ...

• Why are the HCO⁺ peaks outside the inner disk region?

• What do the different molecules imply about the chemistry in this O-rich object?

• Is the gas mostly confined to the axial flow or the lobe walls?

• What are the dust properties in the regions of the HCO⁺ peaks? Have the shocks altered the dust?

Example 2: RNO 91 - a T Tauri star with a (bipolar?) outflow



V image from Scarrott et al. (1990)

- Associated with the L43 dark cloud
- M0.5 T Tauri star
- close (~ 160 pc)
- surrounded by an extensive disk containing H_2O , CO and maybe XCN ices
- large scale bipolar CO outflows
- southern lobe closest ($\theta \sim 36^\circ$)
- superficially similar to OH321.8+4.2

Polarisation associated with Rno 91

- the centro-symmetric pattern is again indicative of scattering by dust
- surprisingly the Rpolarisation map suggests a small disk ~ 4" long in a NW
 SE direction
- is the illuminating source displaced from the optical peak?



from Weintraub et al. 1994

Again, polarimetry and I R imaging (next slide) let us constrain the dust grain properties in different regions of the object (disk, outflows, etc.).

Our observations (IR imaging):



The optical and infrared observations show ...

 many knots, dark lanes and 'fingers' (the southern one is particularly distinct)

• a change in the dust grain size moving away from the central course

no obvious lobes

• the central source appears to be visible and coincident with the northern peak - so the supposed dust lane is not an edge-on disk obscuring the central star.

• are the knots H-H objects, or just structure or clumpiness around RNO 91?

What if we now want to probe the gas at similar resolution?

RNO 91 hasn't yet been observed at the same resolution as OH231.8+4.2





Bence et al. 1998, BIMA array

Optical, infrared and radio observations reveal the morphology of the Rno 91 region:

- CCD images reveal a 'bay' in the L43 cloud, with RNO 91 near its northern end
- RNO 91 is at the junction of blueand redshifted ¹²CO J=1-0 emission
- NH₃ (J,K) = (1,1) emission corresponds to the dense molecular core
- CS J=2-1 peaks at RNO 91
- we see a picture of a young star at the apex of two paraboloidal volumes, embedded in a dense molecular core



from Mathieu et al. 1988

Molecular hydrogen in RNO 91:

What about the suggestion that there might be H-H objects around the RNO 91 core? We might use the ATCA to search for the products of shocks close to the central star. In fact, there is already some evidence of shocks ...

the H₂ v=1-0 S(1) line is detected⁺ with a N-S extent of ~ 9" the H₂ line ratios are consistent with shock excitation rather than fluorescence Are we seeing H₂ emission from embedded H-H like knots?



[†]from Nanda Kumar et al. 1999

What does the central region of an outflow like RNO 91 look like on an arcsecond scale? Can this help us constrain the existing outflow models?

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