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Sculpting a Bipolar Preplanetary Nebula with Highly-Collimated Fast Jets

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Pre-planetary nebulae (PPNe), transition objects between the AGB and Planetary Nebulae (PN) phases, hold the key to understanding how the slowly expanding, largely spherical, circumstellar envelopes (CSEs) of AGB stars transform into highly-aspherical PNs with elongated lobes expanding at high speeds. In 1998, Sahai & Trauger proposed that, as stars evolve off the AGB, they drive collimated fast winds that sweep up and shock the AGB CSE, producing the observed dramatic change in circumstellar geometry and kinematics. The PPN, IRAS 22036+5306 (I22036) offers exciting support for this hypothesis. Its highly structured morphology in HST images, and CO $J = 3 - 2$ interferometric mapping, show that fast (~200 km/s), collimated jet-like outflows are actively sculpting the CSE into a bipolar PPN. I22036 is thus a key object in clarifying the physics of the transition to bipolarity at the beginning of post-AGB evolution.

We present the results of a multiwavelength study of I22036. New HST Hα and [O *i*] emission-line images clearly delineate the active shocks, and deep broad-band images reveal point-symmetric ansae beyond the tips of the main bipolar lobes, an extended round halo representing the remnant AGB CSE, and the central star. Optical long-slit (echelle) spectroscopy with the Keck/ESI shows the detailed kinematical structure of the shocked regions. Near-IR (1.1–2.4 μm) spectroscopy of I22036 using the Palomar 200-inch/TripleSpec spectrograph shows strong H2 (δV = 1) emission from shocked molecular gas in a bipolar outflow. Prominent CO (δV = 2) bandheads are seen in emission towards the center, indicating very hot (>few $\times$ 1000 K) gas in a disk or outflow.

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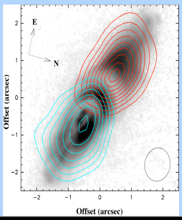

Fig. 2a. Bipolar Molecular Outflow in I22036, mapped in CO J=3-2 with the SMA [Setal06]

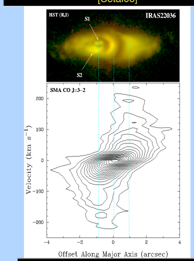

Fig. 2b. PV plot of the CO J=3-2 emission along I22036's major axis [Setal06]

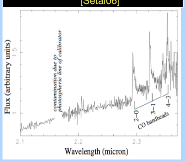

Fig. 4a. CO ΔV=2 emission bandheads towards the central source with TSPEC

1. Introduction:

Pre-planetary nebulae (PPNs), short-lived transition objects between the AGB and Planetary Nebulae (PN) phases, hold the key to understanding how the slowly expanding, largely spherical, circumstellar envelopes (CSEs) of AGB stars transform into highly aspherical PNs with elongated lobes expanding at high speeds (e.g., review by Balick & Frank 2002).

Sahai & Trauger (1998) proposed that, as stars evolve off the AGB, they drive collimated fast winds that sweep up and shock the AGB CSE, producing the observed dramatic change in circumstellar geometry and kinematics.

The PPN, IRAS22036+5306 (I22036) offers an exciting opportunity to test this hypothesis. Its highly structured morphology in HST images (Sahai et al. 2003 [Setal03]; Fig. 1), and interferometric mapping of OH masers (Setal03; Fig 1) and CO J=3-2 (Sahai et al. 2006 [Setal06]; Fig 2ab), showed that fast (~200 km/s), collimated jet-like outflows are actively sculpting the CSE into a bipolar PPN. A dusty waist harbors a substantial mass of very large (~1 mm) grains (Setal06).

I22036 is thus a key object in clarifying the physics of the transition to bipolarity at the beginning of post-AGB evolution. Here we report results from new observations, which include deep broad-band and narrow-band imaging with HST/HRC and ground-based spectroscopy.

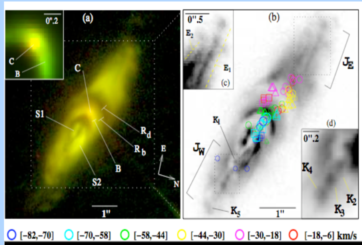

Fig. 1. HST/WFPC2 image and OH maser emission from I22036 (from Sahai et al. 2003), showing a bipolar PPN with knotty jets. The OH masers, grouped into 6 color-coded velocity bins, showed the presence of a high-velocity outflow

2. Observational Results:

2.1. ACS Imaging

(1) Deep 0.8 micron (F814W) image reveals diffuse round halo around the nebula (Fig. 3). The central star is clearly seen.
The halo represents the spherical mass-loss during the AGB phase of the central star.

The halo radial brightness distribution is a segmented power law, with a power-law index β~2.3 (4.4) describing an inner region, r < 3" (outer region, r > 3"). Assuming the same expansion velocity for these regions, we infer that the mass-loss rate went through a maximum (Sahai et al. 2007).

(2) Hα+[NII] (F658N) images show two compact emission peaks representing newly shocked gas in the knotty jet in each lobe (Fig. 3). The inner peaks are located at radial offsets of (1.5-1.6) arcsec from the center, and are also the sites of strong emission in near-IR and optical line tracers of shocked gas (*see Spectroscopy section below*).

Fig. 3 .HST/ACS image of I22036 (red: F814W, green: F606W, blue: F658N)

2.2. Spectroscopy

(A) NIR (1-2.4 μm) spectroscopy using the Mt. Palomar 200-in/TSPEC instrument (1-2.4 micr)

(1) Strong CO ΔV=2 bandheads are seen towards the star (Fig. 4a) signifying the presence of extremely hot gas (>few x 1000 K). Does this arise in an accretion disk (as seen in YSOs) or an outflow? High spatial-resolution observations are needed!

(2) Strong vibration-rotation line emission from shocked molecular H_2 from two blobs spatially offset from the star (Fig. 4b shows the 2.1 micron line); the emission is Doppler shifted from the systemic velocity by +/-140 km/s. These blobs are associated with regions S1,S2 in the near-lobe and their counterpart in the far lobe.

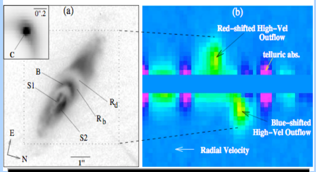

Fig. 4b. H2 emission from shocked gas in the high-velocity outflow; blue- and red-shifted components are separated by 280 km/s

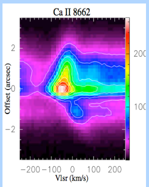

Fig. 5a. CaII emission scattered off dust in high-velocity outflow

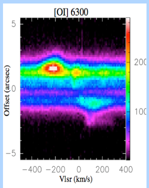

Fig. 5b. [OI] emission from high-velocity shocked gas

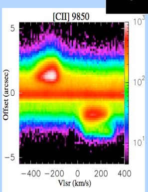

Fig. 5c. [CII] emission from high-velocity shocked gas

(B) Optical spectroscopy with the Keck ESI instrument (3900-10900 A)
[first results from optical spectroscopy (Sahai et al. 2003,2006, S'anchez Contreras et al. 2008) showed that I22036, like many other PPNs, shows a "P Cyg" type Hα profile, with very wide wings, FWZI~2500 km/s]

(1) Strong emission in the CA II triplet (8498,8542,8662 A) is observed (e.g., Fig. 5a). These lines, like the H recombination lines (Balmer, Paschen series) show a characteristic red-shifted signature due to scattering by a dusty outflow.
Model with *Vexp ~ r* provides a good fit to the PV data (Fig. 5a), and yields an inclination angle of 59 deg for the outflow axis, relative to the line-of-sight. The inclination angle is critical for determining the 3D outflow velocity (345 km/s), the distance to I22036 from measurements of proper motion in the outflow, and the momentum of the molecular outflow.

(2) Nebular emission is seen in forbidden lines such as [SII] 6716,6731, [OI] 6300, and [CII] 9824,9850 (Fig. 5b,c). This emission (like in the 2 micr H_2 lines) arises in two blobs spatially offset from the star by ~1.5", associated with the regions S1,S2 and their far-lobe counterparts.
The [CII] emission is very strong. These lines are commonly seen in supernova shocks. None of the other PPNs in our survey (S'anchez Contreras et al. 2008) show obvious emission in these lines.

3. SUMMARY

We have presented results from a new multi-wavelength study of a key object in probing the transition to bipolarity at the beginning of post-AGB evolution - the bipolar PPN, I22036.
The observations show an unprecedented detailed view of a spherical AGB envelope being transformed into a bipolar PPNs via very fast jets during the early post-AGB phase.
All three components of the transformation (envelope, jets, sculpted lobes) are clearly seen.
We have determined the inclination of the outflow and its 3D speed (345 km/s). These data provide the information for building and testing detailed theoretical models of the jet-envelope interaction.

4. FUTURE WORK

We are carrying out multiwavelength continuum observations with the VLA order to probe large grains in the dusty waist region.
We have a scheduled Cycle 17 STIS program to map the Hα emission at high spatial resolution and adequate spectral resolution using STIS.
We plan to use integral-field-spectrographs such as OSIRIS/Keck behind AO to map the CO ΔV=2 bandhead emission with high spatial and spectral resolution, and determine if they are associated with an outflow or a disk.

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