AN EXTREME HIGH-VELOCITY BIPOLAR OUTFLOW IN THE PRE-PLANETARY NEBULA IRAS 08005-2356

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ABSTRACT

We report interferometric mapping of the bipolar pre-planetary nebula IRAS 08005-2356 (108005) with an angular resolution of ~1″–5″, using the Submillimeter Array, in the 12CO J = 2–1, 3–2, 13CO J = 2–1, and SiO J = 5–4 (v = 0) lines. Single-dish observations, using the SMT 10 m, were made in these lines as well as in the CO J = 4–3 and SiO J = 6–5 (v = 0) lines. The line profiles are very broad, showing the presence of a massive (>0.1 M⊙), extreme high velocity outflow (V ~ 200 km s⁻¹) directed along the nebular symmetry axis derived from the Hubble Space Telescope imaging of this object. The outflow’s scalar momentum far exceeds that available from radiation pressure of the central post-AGB star, and it may be launched from an accretion disk around a main-sequence companion. We provide indirect evidence for such a disk from its previously published, broad Hα emission profile, which we propose results from Lyβ emission generated in the disk followed by Raman-scattering in the innermost regions of a fast, neutral wind.

Key words: accretion, accretion disks – circumstellar matter – planetary nebulae: individual (IRAS08005-2356) – stars: AGB and post-AGB – stars: mass-loss – stars: winds, outflows

1. INTRODUCTION

Following the ejection of half or more of their mass via isotropic, slowly expanding winds, AGB stars evolve into planetary nebulae (PNe), which, surprisingly, show a diverse range of aspherical (e.g., bipolar and multipolar) morphologies (e.g., Sahai & Trauger 1998; Sahai et al. 2011c). Studies of pre-planetary nebulae (PPNe), objects in transition between the AGB and planetary nebula (PN) evolutionary phases, are critical for characterizing the physical processes responsible for this dramatic transformation. Sahai & Trauger (1998) proposed that fast collimated outflows or jets, operating during the PPN and/or very late AGB phase, are the primary agents for the dramatic change in the mass-loss geometry and dynamics during the AGB-to-PN evolutionary phase. However, the physical mechanism for producing these fast outflows remains a mystery. High angular resolution interferometric (sub)millimeter-wave observations are the best way to quantitatively probe the fast outflow’s dynamics and energetics—crucial information for theoretical models (e.g., Akashi & Soker 2013), and detailed numerical hydrodynamical simulations (e.g., Lee & Sahai 2003; Balick et al. 2013), for PN shaping.

Such observations have resulted in the discovery of a handful of “extreme-outflow” PPNe—objects in which the molecular outflows reach speeds in excess of ~100 km s⁻¹, e.g., Boomerang Nebula (Sahai et al. 2013), IRAS 22036+5306 (Sahai et al. 2006), IRAS 19374+2359 (Sánchez Contreras et al. 2013), IRAS 16342-3814 (Imai et al. 2012), and HD 101584 (Olofsson et al. 2015). Detailed studies of such extreme objects are likely to provide the best motivation for, and most stringent tests of, theoretical models to explain their origin (e.g., Blackman & Lucchini 2014).

In this Letter, we report (sub)millimeter-line observations of the PPN IRAS 08005-2356 (108005), which clearly reveal it to be an extreme-outflow PPN. Early CO J = 2–1 observations by Hu et al. (1994) resulted in the marginal detection of a weak, broad line. I08005’s F5 Ie central star V510 Pup (Slijkhuis et al. 1991) may have made a recent transition from ejecting oxygen-rich material to carbon-rich material (Bakker et al. 1997). Its morphological classification is Bo*(0.55) (Sahai et al. 2007), i.e., it has a bipolar morphology (resolved via Hubble Space Telescope (HST) imaging; Ueta et al. 2000) with lobes open at their ends and a central star seen at 0.55 μm. Its optical spectrum reveals the presence of a prominent Hα emission line with very broad wings (FWZI ~ 2400 km s⁻¹) and a P-Cygni-type blueshifted absorption feature (Sánchez Contreras et al. 2008, hereafter SánchezContreras 2008; also Slijkhuis et al. 1991; Klochkova & Chentsov 2004). Its estimated distance ranges between 2.85 kpc (Oppenheimer et al. 2005, OBS05) and 3–4 kpc (Klochkova & Chentsov 2004); we adopt a value of 3 kpc.

2. OBSERVATIONS

The 1.3 and 0.87 mm interferometric observations were obtained with the Submillimeter Array (SMA) at Mauna Kea, Hawaii. Bandpass calibration was performed using observations of 3C279. At 1.3 (0.87) mm, complex gain calibration was obtained from observations of the quasars 0750+125 and 0730–116 (0747–331 and 0826–225), and flux calibration was obtained from observations of Callisto (Europa). Additional observing parameters are listed in Table 1.

SMA data were calibrated using the MIRIDL package, and images were made using the Miriad software. Data cubes were obtained with a velocity resolution smoothed to 10 km s⁻¹ per channel (to increase the signal-to-noise ratio (S/N) in each channel). Natural weighting was used to produce all images.

Single-dish observations of the 12CO J = 2–1, 3–2, and 4–3; 13CO J = 2–1; and SiO (ν = 0) J = 5–4 and 6–5 line emission were obtained at SMT during 2014 November/December and 2015 January. Telescope pointing was frequently checked on VY CMa and is estimated to be better than a small fraction of the beam. The weather was generally good, with system

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3 The SMA is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

4 http://www.cfa.harvard.edu/~cqi/mircook.html
temperatures in the range $T_{\text{sys}} \sim 200–250$ K at 1.3 mm and $T_{\text{sys}} \sim 1300$ K at 0.7 and 0.8 mm. Linear baselines were subtracted from the spectra shown. We have assumed main-beam efficiency factors of 0.76, 0.66, and 0.62 for the 230.6, 345.8, and 461.0 GHz observations (Edwards et al. 2014).

The optical images were taken with the NASA/ESA HST in GO programs ID 6364 (PI: M. Bobrowsky) and 6366 (PI: S. Trammell), using the PC on WFPC2, and extracted from the Hubble Legacy Archive.

3. RESULTS

3.1. Optical Imaging

I08005 shows an hourglass morphology in the HST F439W, F555W, and F675W images (Figure 1)—the lobes, separated by a narrow dark lane, flare out from the central star’s location and attain a cylindrical shape. The SE lobe is significantly brighter than the NW one. A narrow, slightly curved feature of linear extent 0″.38 is seen extending from the central star in the SE lobe (see the inset). The feature is oriented at a PA = 120°, different from the PA of the nebula symmetry axis, PA = 143°. The total linear extent of the nebula along its long axis, as seen in the F555W image, is $\sim 2″.6$ ($1.2 \times 10^{17}$ cm).

3.2. Millimeter-wave Observations

We detected the CO $J = 2–1, 3–2$ and SiO $J = 5–4$ lines with the SMA. The CO $J = 3–2$ and SiO $J = 5–4$ have significantly lower signal-to-noise, and the $^{13}$CO $J = 2–1$ is tentatively detected. The (spatially) integrated SMA CO $J = 2–1$ line profile (using a 15″ diameter circular aperture) shows a very broad profile (Figure 2) covering a total velocity extent of about 350 km s$^{-1}$, i.e., from $-150 < V_{\text{lsr}}$ (km s$^{-1}$) $\leq 200$. The SMT CO $J = 2–1$ line profile (Figure 2) is similar to the SMA one (a narrow emission feature at $V_{\text{lsr}} = 36$ km s$^{-1}$ due to the presence of an unrelated line-of-sight interstellar cloud has been removed from the profile by interpolation). A Gaussian fit to the profile gives a central velocity $V_{\text{lsr}} \sim 25$ km s$^{-1}$ and an FWHM of 196 km s$^{-1}$.

We have divided the velocity range spanned by the CO $J = 2–1$ line into three intervals on each side of the central velocity—the extreme high-velocity (EV) component (blue: $-150 < V_{\text{lsr}}$ (km s$^{-1}$) $< -85$, red: $130 < V_{\text{lsr}}$ (km s$^{-1}$) $< 200$), a medium-velocity (MV) component (blue: $-85 < V_{\text{lsr}}$ (km s$^{-1}$) $< -30$, red: $70 < V_{\text{lsr}}$ (km s$^{-1}$) $< 130$), and a low-velocity (LV) component (blue: $-30 < V_{\text{lsr}}$ (km s$^{-1}$) $< 25$, red: $25 < V_{\text{lsr}}$ (km s$^{-1}$) $< 75$). The SMA CO $J = 2–1$ emission in the blue- and redshifted parts of the EV, MV, and LV components...
show separations of about 2″1, 1″1, and 0″5, respectively, along the nebular symmetry axis (Figure 3(a)).

These results imply the presence of a fast, bipolar outflow with a (roughly) linear velocity-gradient, directed along the nebular symmetry axis, and a linear extent of ∼2″1. Since AGB mass loss is typically spherical, with outflow velocities of 10–15 km s⁻¹, we conclude that the outflow observed in CO J = 2–1 is a fast, collimated post-AGB outflow, typical of the PPN evolutionary phase. We made similar plots from the SMA data cubes for CO J = 3–2 (Figure 3(b)) and SiO J = 5–4 (not shown), dividing the emission velocity-range into two halves only (blue: −90 < Vₗsr (km s⁻¹) < 20; red: 30 < Vₗsr (km s⁻¹) < 130) due to the lower S/N in these lines and found that these show a separation of 0″85 roughly along the nebular axis. This separation is equal to that derived from our CO J = 2–1 data for the same red and blue outflow velocity ranges, implying that the SiO outflow’s linear extent is likely comparable to that of CO.

We also detected the CO J = 4–3, J = 3–2, and ¹²CO J = 2–1 as well as the SiO (ν = 0) J = 5–4 and 6–5 lines with the SMT, but with lower S/N (Figure 2). We have compared the total CO J = 2–1 line fluxes from our SMA and SMT data, as these have the highest S/N, and find that these are consistent within 15%, i.e., within typical calibration uncertainties—we conclude that the SMA data do not suffer from any significant flux losses.

Continuum images were obtained after removing spectral regions containing line emission using the Miriad task uvlin. No continuum emission was detected from I08005. Using line-free channels, we find a 1σ noise of 1.05 (1.2) mJy beam⁻¹ in the USB (LSB) at 1.3 mm and 11 (18) mJy beam⁻¹ in the USB (LSB) at 0.87 mm.

Figure 2. Molecular-line emission from I08005. The SMT spectra (shown above Vₗsr = 0 axis) have been shifted vertically for clarity, after scaling as follows: SiO J = 6–5 and J = 5–4 (x4), ¹²CO J = 4–3 and 2–1 (x2), and ¹³CO J = 2–1 (x10). The velocity ranges of the HV, MV, and LV components are marked in the SMA panel. The SMA ¹²CO J = 2–1 spectrum, shifted below Tₚ = 0, shows the total flux divided by the SMT conversion factor of 44.5 Jy K⁻¹, then scaled ×2, for comparison with the SMT spectrum. The apparent difference in the SMT and SMA CO J = 2–1 line profiles at Vₗsr ∼ 100 km s⁻¹ is probably due to nonlinear baseline structure that is not removed by the linear baseline subtraction.

Figure 3. SMA CO emission integrated over different velocity (Vₗsr) ranges (a) J = 2–1: (top) blue: −150, −85; red: 130, 200; (middle) blue: −85, −50; red: 70, 130; (bottom) blue: −30, 25; red: 25, 75. (b) J = 3–2: blue: −90, 20, red: 30, 130. Contour levels for CO J = 2–1 (3–2) are: minimum = 50 (46)% of the peak intensities. The central source in the HST image (marked with a cross) is offset (0″041, 0″4) relative to the phase center (at 0.0 with J2000 coordinates R.A. = 08:02:40.7, decl. = −24:04:43.0) and consistent with the bipolar-outflow center, within the combined 1σ uncertainty, ∼(±0″4, ±0″4), of the absolute HST and SMT astrometry.
4. THE POST-AGB BIPOLAR OUTFLOW

4.1. Outflow Properties

We now determine the physical properties of the high-velocity bipolar outflow (e.g., scalar momentum, mass, and age) from an analysis of the molecular-line data. The observed ratios of the CO J = 2–1, 3–2, and J = 4–3 fluxes (in K km s$^{-1}$) are 1:1.27:1.2, which imply corresponding non-beam diluted flux ratios of $R_{32/21}$/$R_{33/22}$ = 1.0:6.0:0.3 since the source is unresolved by the SMT beams of 32", 22", and 16" in these lines.

We first make a simple emission model assuming a spherical outflow at a uniform excitation temperature equal to the kinetic temperature, $T_{\text{kin}}$, and carry out a least squares fit to the line fluxes, varying $T_{\text{kin}}$, the outer radius ($R_{\text{out}}$), and the mass of the emitting region ($M_{\text{e}}$). We find $R_{\text{out}}$ = 174" and $T_{\text{kin}}$ = 13.6 K. However, the derived $T_{\text{kin}}$ is rather low compared to energy of the CO J = 4 level (55.4 K), and modeling with the non-LTE RADEX code (van der Tak et al. 2007) shows that the J = 4–3 excitation temperature, $T_{\text{ex}(43)}$, is lower than $T_{\text{kin}}$ by about (20–25)% due to the relatively low CO line optical depths in our model ($<0.01$) and the average density, $n_{\text{av}} \sim 3.5 \times 10^4$ cm$^{-3}$, implied by the emitting region’s mass and volume. Thus, the resulting, corrected model $R_{32/21}$ ~ 0.11 is too low to fit the data.

Using RADEX, we find that the average density required to bring $T_{\text{ex}(43)}$ closer to $T_{\text{kin}}$ in order to fit the observed source brightness temperature ratios is $n_{\text{av}} > 7.5 \times 10^4$ cm$^{-3}$; the required $T_{\text{kin}}$ = 15.5 K, giving a source size of 274", comparable to the CO source size estimated from the SMA data. The model source size is similar to the size derived from the HST image, implying that the CO emission likely comes from the dense walls of the bipolar lobes seen in scattered light. The CO column density is $N_{\text{CO}} > 5 \times 10^{17}$ cm$^{-2}$ (and the J = 2–1, 3–2, and 4–3 lines have optical depths of 0.48, 0.44, and 0.20). Assuming that the average emitting column is equal to the source radius, we find a CO-to-H$_2$ abundance ratio of, $f_{\text{CO}} = 1.3 \times 10^{-4}$, in reasonable agreement with the value typically assumed for PPNe, 2 $\times$ 10$^{-4}$ (e.g., Bujarrabal et al. 2001). Assuming a spherical emitting volume, the mass is $M_{\text{e}}$ = 0.076 $M_\odot$. The $^{12}$CO/$^{13}$CO abundance ratio is $f$ ($^{12}$CO/$^{13}$CO) = 9.6 from fitting the $^{12}$CO/$^{13}$CO J = 2–1 line flux ratio corrected for the different beam dilutions (8.1).

The above values of $M_{\text{e}}$ and $f$ ($^{12}$CO/$^{13}$CO) are lower limits since this is our “minimum-mass” model—models with higher values of $n_{\text{av}}$ are allowed. However, the total mass increases more slowly than the average density since in models with higher values of $n_{\text{av}}$, the emitting region’s size is smaller. For example, if we use the dust mass $M_d$ = 0.0019 $L_\odot$ (D/$2.85$ kpc$^2$) derived by OBS05 from a detailed 2D radiative transfer model of I08005’s SED, scale it to $D$ = 3 kpc, and adopt a typical gas-to-dust ratio for oxygen-rich AGB stars $M_d$/$M_d$ = 200, we get $M_{\text{e}}$ = 0.42 $M_\odot$. For this value of $M_{\text{e}}$, we need a CO model with $n_{\text{av}} \sim 8 \times 10^4$ cm$^{-3}$, a factor of $\sim 10$ higher than in our minimum-mass model; $T_{\text{kin}}$ = 11.5 K, and $N_{\text{CO}} = 1.6 \times 10^{18}$ cm$^{-2}$. Since the CO J = 2–1 optical depth is higher ($\tau_{21}$ = 1.95), the abundance ratio is higher, $f$ ($^{12}$CO/$^{13}$CO) = 17.

We calculate the scalar momentum using the formulation described in Bujarrabal et al. (2001). Using our minimum-mass model, we find $P_{\text{sc}} \sim 2.8 \times 10^{39}$ g cm s$^{-1}$ for an inclination angle of the nebular axis to the sky plane, $i = 30^\circ$ (OBS05). The kinetic energy in the outflow is $E_{\text{kin}} \sim 2.6 \times 10^{45}$ erg. These values of $P_{\text{sc}}$ and $E_{\text{kin}}$ lie near the upper end of the range for PPNe, 10$^{39}$–3$\times$10$^{46}$ erg (Bujarrabal et al. 2001).

This outflow cannot be driven by radiation pressure because the lobes’ dynamical (expansion) timescale $t_{\text{dyn}}$ is 190 years (from dividing the model CO shell size by the CO J = 2–1 FWHM line width) is much smaller than that required by radiation pressure to accelerate the observed bipolar outflow to its current speed, $v_{\text{out}} = P_{\text{sc}}/(L/c) \sim 6.6 \times 10^4$ years, given I08005’s luminosity of 6980 $L_\odot$ at $D = 3$ kpc (using the value derived by OBS05, 63000(D/2.85 kpc)$^2$ $L_\odot$). The mass-loss rate in the outflow is $\sim 5.8 \times 10^{-4} M_\odot$ yr$^{-1}$.

The observed SMT SiO J = 6–5 to 5–4 line flux ratio is 0.94 (with about ±15% uncertainty), implying an intrinsic flux ratio (i.e., corrected for beam dilution) of $R$(SiO)$_{65/54}$ = 0.66 since the source is unresolved by the SMT beams of 34" and 28". The values of $R$(SiO)$_{65/54}$ are closely associated. The atomic gas may be located inside the lobes walls, as proposed for IRAS 22036+5306 (Bujarrabal & Bieging 1993). If the SiO emission comes from shocked gas at a higher kinetic temperature than that for CO, the minimum density required is higher.

4.2. A Central Accretion Disk?

Evidence of very fast outflows in I08005 comes from three independent probes: (i) CO data (presented here), (ii) H$\alpha$ spectrum in SCetal08, and (iii) OH maser emission (VLA mapping) reported in Zijlstra et al. (2001). The OH maser features cover the velocity range of 0 < $V_{\text{hel}}$ (km s$^{-1}$) < 100, i.e., roughly the range covered by the red half of the CO J = 2–1 profile. In contrast to OH and CO emission, the H$\alpha$ absorption probes atomic gas. Since the H$\alpha$ absorption feature is not spatially resolved in the ground-based long-slit spectra, it is difficult to directly establish its relationship to the fast molecular outflow; however, the close agreement between the terminal outflow velocities derived for these indicates that they are closely associated. The atomic gas may be located inside the lobes and may constitute unshocked material of an underlying jet and/or the interface between the latter and the lobe walls, as proposed for IRAS 22036+5306 ( Sahai et al. 2006). The jet-like feature seen in the HST image (Figure 1, inset) may represent the precessing jet’s signature close to its launch site.

The high-speed bipolar outflow in I08005 may be driven by an accretion disk. Bakker et al. (1997) find numerous narrow, double-peaked, chromospheric emission lines from neutral and singly ionized metals and propose that these might arise in an accretion disk. We conjecture that the broad H$\alpha$ wings seen toward this object might arise as a result of Raman-scattering of Ly$\beta$ emission generated by such a disk—a process that produces an H$\alpha$ profile with a width that is a factor 6.4 larger than the Ly$\beta$ width and a $\lambda^{-2}$ wing profile. The very wide (FWZI ~ 2400 km s$^{-1}$) H$\alpha$ line wings in I08005 show this shape; furthermore, a weak emission feature around 6830 Å with FWZI ~ 150 km s$^{-1}$, corresponding to Raman-scattering of the 1032 Å component of the O VI doublet at $\lambda\lambda$1032, 1038.
is also seen (SCetal08). The 7088 Å feature that corresponds to the 1038 Å component is a factor of four weaker and too weak to be visible.

Other line-broadening mechanisms include electron scattering and emission from a rotating disk. Arrieta & Torres-Peimbert (2003) find that electron scattering requires extreme densities (e.g., \( n_e > 10^{12} \text{ cm}^{-3} \) in M 2–9), making an implausible mechanism. Keplerian rotation in a disk around the central star is too low to directly account for the broad line-width in I08005 (and PPNe in general; Sahai et al. 2011b)—taking the radius for the central post-AGB star of I08005 to be \( R \sim 50 R_\odot \) (Slijkhuis et al. 1991) and a nominal stellar mass of \( 1 M_\odot \), we find the maximum rotation speed is \( v_{\text{max}} \ll 56.5 \text{ km s}^{-1} \), too low for generating the extreme line wings of the \( \text{H}_\alpha \) profile, even with the factor of 6.4 increase provided by Raman-scattering. We therefore conclude that the accretion disk in I08005 must be around a much smaller star, e.g., a main-sequence companion.

The Raman-scattering likely occurs in the innermost regions of the fast neutral wind seen via its blueshifted absorption feature signature in the \( \text{H}_\alpha \) profile. In this case, following Sahai et al. (2011b), we scale from the minimum scattering column density, \( N_e = 10^{19} - 20 \text{ cm}^{-2} \), needed to achieve the Raman conversion efficiency necessary for producing the very broad observed line-widths (see Figure 1 of Lee & Hyung 2000) to find that \( dM_\exp/dt > (0.35 - 3.5) \times 10^{-4} M_\odot \text{ yr}^{-1} (n_e/30 \text{ AU}) \) \((D/3 \text{ kpc}) \times (V_{\text{exp}}/100 \text{ km s}^{-1}) (N_e/10^{19} \text{ cm}^{-2}) \), where \( r_e \) is the radius of the neutral wind where the Raman-scattering occurs. \( V_{\text{exp}} \) set equal to 0.5 × FWHM of the broad CO \( J = 2 \rightarrow 1 \) line profile and similar to the neutral outflow’s average outflow-velocity derived by SCetal08. The mass-loss rate requirement is easily met in I08005 since OBS05 derive a mass-loss rate of 4.4 \( \times 10^{-4} M_\odot \text{ yr}^{-1} \) for a collimated fast wind in the 24–780 AU region around the central star.

## 5. DISCUSSION

I08005 is very similar to other extreme-outflow oxygen-rich PPNe, IRAS 22036+5306 and HD 101584 (Sivarani et al. 1999; Olofsson et al. 2015), in the properties of its collimated fast outflow (expansion velocity, scalar momentum, and kinetic energy) and its \( \text{H}_\alpha \) emission profile (very broad wings, P-Cygni absorption). However, in striking contrast to these objects, it appears to lack millimeter and submillimeter continuum emission from its central region—the ratio of its 1.3 mm to 60 \( \mu \text{m} \) flux is \(< 10^{-4} \) (3\( \sigma \)), compared to 0.6 \( \times 10^{-3} \) and 1.5 \( \times 10^{-3} \) for HD 101584 and IRAS 22036+5306 (Sahai et al. 2006), respectively.

Both PPNe, as well as the “disk-prominent” sub-class of young post-AGB objects (dp-AGB objects; Sahai et al. 2011a), which, unlike PPNe, show little or no extended nebulosity and have central stars that are radial-velocity binaries (e.g., van Winckel et al. 2008), emit relatively strong millimeter/submillimeter continuum emission from their central regions. This emission has been attributed to the presence of substantial masses of cool, millimeter-sized grains (de Ruyter et al. 2006; Gielen et al. 2007; Sahai et al. 2011a). Their origin is not understood at present but is potentially a key probe of important mass-ejection processes occurring during the late-AGB and post-AGB evolutionary phases, especially those that lead to the formation of large dusty equatorial disks or tori. For example, in HD 101584, where a binary companion has been found from radial-velocity variations (Bakker et al. 1997), Olofsson et al. (2015) propose a scenario in which both the formation of the central, equatorially dense mass structure, and the collimated outflow result from a common-envelope (CE) event—but the latter does not release enough energy to drive the mass ejection, and another mechanism augments or even dominates it.

The apparent lack of a substantial mass of material in the equatorial waist of I08005 suggests that perhaps it did not undergo a CE event, and its collimated outflow (and collimated outflows in PPNe generally) may be launched differently, possibly from an accretion disk as we have suggested earlier. I08005 is thus a key post-AGB object for further detailed study. For example, ALMA can be used to probe its compact central region in order to search for weak millimeter/submillimeter continuum emission that may be present, but was below our sensitivity limit, and for the presence of gas (and its kinematics) associated with its dusty waist.

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