Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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High angular-resolution infrared imaging and spectra of the carbon-rich AGB star V Hya

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Abstract. The carbon-rich AGB star V Hya is believed to be in the very brief transition phase between the AGB and a planetary nebula (PN). Using HST/STIS, we previously found a high-velocity ($>200\,\mathrm{km s^{-1}}$) jet or blob of gas ejected only a few years ago from near (<0.3 arcsec or 150 AU) the star (Sahai *et al.* 2003, Sahai *et al.* 2016). From multi-epoch high-resolution spectroscopy we found time-variable high-velocity absorption features in the CO 4.6 μm vibration-rotation lines of V Hya (Sahai *et al.* 2009). Modeling shows that these are produced in compact clumps of outflowing gas with significant radial temperature gradients consistent with strong shocks. Here, we present very high resolution (∼100 milliarcsecond) imaging of the central region of V Hya using the coronagraphic mode of the Gemini Planet Imager (GPI) in the 1 μm band and spectral-spatial imaging of 4.6 μm CO 1-0 transitions using the Phoenix spectrometer. We report the detection of a compact central dust disk from GPI, and molecular emission from the Phoenix observations at relatively larger scales. We discuss models for the central structures in V Hya, in particular disks and outflows, using these and complementary images in the optical and radio.

Keywords. stars: AGB and post-AGB, instrumentation: High angular resolution, ISM: planetary nebulae: general

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1. Mid-IR Imaging and Spectra

Fig. 1 shows Y band coronagraphic images of V Hya using GPI: the total intensity, polarized intensity and polarized fraction. The white circle marks the extent of a 0.57" (285 AU at a distance of 478 pc to V Hya) disk inferred by Townes *et al.* (2011) through mid-IR interferometry. The disk is clearly detected in the GPI polarized (scattered) light image. In our model the star is located at the center of a flared thick disk structure tilted such that its west side opens towards us (Fig. 2). In the GPI image, we are seeing light scattered from the surface of this disk, but only (the more distant) half of this disk is seen, from where the starlight is back-scattered towards us. As the disk is optically thick, and because it has a highly flared geometry, the illuminated part of its near side is not exposed to us directly. This explains why the disk-light is seen only on one side of the star.

Fig. 2 shows a schematic for the inner region of V Hya, with an equatorial, slowly expanding CO region, compact central dust disk and fast, clumpy bipolar outflows. The fast "bullets" close to the star have been detected in SII with HST/STIS (Sahai *et al.*

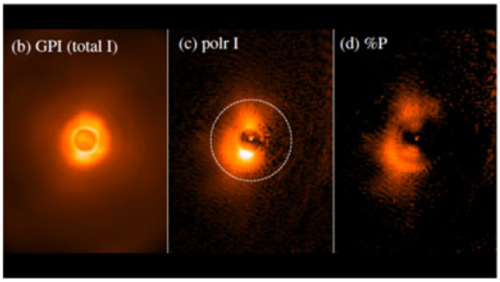

Figure 1. Y band coronagraphic images of V Hya with GPI. North is up, east to the left.

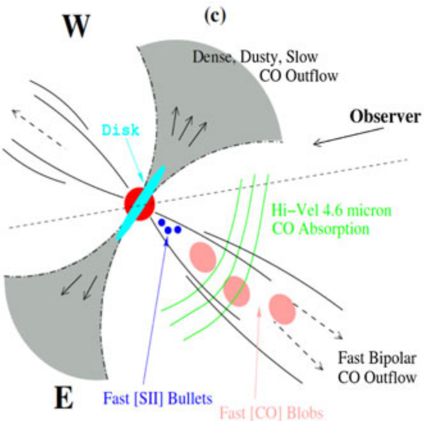

Figure 2. Schematic view of the central structures and outflows.

2003, Sahai *et al.* 2016, Scibelli *et al.* 2018) and the clumpy bipolar CO outflow with the SMA and IRAM 30m (Hirano *et al.* 2004, Kahane *et al.* 1995). For scale, the "bullets" are < 0.3" or 150 AU offset from the star, and the dense slow outflow (grey) is about 10" in extent on each side (not shown in full).

We detect both slow and fast outflows in spectra of the 4.6 μm CO band using Phoenix at Gemini with the slit offset by 0.5" south from the star and after subtracting the stellar continuum. An average of the 1-0 R1, R2, and R3 lines in emission shows a low velocity peak consistent with the normal, slowly expanding circumstellar envelope (CSE) and a high velocity peak at $\sim$ -110 kms^{-1}. This flow is seen to varying degrees in other offsets as well.

2. Summary

We show here high resolution coronagraphic images and spectra of the carbon-rich AGB star V Hya. These are part of a multiwavelength study of V Hya that builds a picture of the CSE of this star caught in transition from the AGB phase to a Planetary Nebula. There is now convincing evidence that V Hya has a slowly expanding equatorial torus (in CO and dust), a compact central disk (dust) and fast blobs or "bullets" (seen in SII and FeII) close to the star aligned with a fast, clumpy, bipolar flow seen at larger distances in CO. Sahai *et al.* (2016) propose an eccentric, 8.5 year period binary system as the engine for the outflow. Periastron passages by the companion through the outer envelope of the primary drive instabilities in the companion accretion disk and eject the collimated "bullet" outflow. These outflows are seen in other similar systems, and the V

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Hya model is likely a common path from a symmetric AGB CSE to a bipolar (perhaps even multipolar) Planetary Nebula.

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