Why Galaxies Care About AGB Stars: A Continuing Challenge through Cosmic Time
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A Tough Egg to Crack

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Abstract. The sculpting of the Egg Nebula continues to defy a coherent explanation. Bipolar outflows from the center of the nebula have created bipolar optical lobes that are illuminated by searchlight beams; multiple bipolar outflows orthogonal to the lobes create the appearance of a dark lane; and quasi-circular arcs are imprinted on an approximately spherically-symmetric wind from the progenitorAGB-star. Here, we use archival data from ALMA to study at high angular resolution dust and molecular gas at the center of the nebula. We find that: (i) dust is concentrated in multiple blobs that outline the base of the northern optical lobe; (ii) dense molecular gas forms the wall of a channel swept up and compressed by the outflows that created the bipolar optical lobes; (iii) the expansion and illumination center of the nebula lies at or close to center of the outflow channel. We present a simple working model for the Egg Nebula, and highlight the difficulties that any model face for explaining all the features seen in this nebula.

1. Introduction

Figure 1 shows a 1.1 μm/1.6 μm image of the Egg Nebula taken with the HST/WFC3 by Balick *et al.* (2012). The most prominent feature is a pair of optical lobes, which have an expansion age of ∼250 yrs (Ueta *et al.* 2006; Balick *et al.* 2012). From HST/WFC2 images, Sahai *et al.* (1998a) had earlier found that the bipolar optical lobes are illuminated at their edges by a pair of searchlight beams emanating from an obscured post-AGB star. They suggested that a precessing bipolar outflow has punched annular holes in a dust cocoon around this star, through which light from the star escapes. This outflow also swept up material in the surrounding envelope to create the bipolar lobes seen in scattered light. At the outer tips of both bipolar optical lobes, Sahai *et al.* (1998b) found line emission at 2.122 μm from molecular hydrogen (H_2). They suggest that the H_2 emission originates from shocked gas at the interface where the bipolar outflow slams into a slower wind ejected when the star was on the AGB. Confirming but also complicating this picture, observations in CO(2-1) by Cox *et al.* (2000) reveal not just one but multiple bipolar outflows along the bipolar optical lobes. Indeed, studies of the spatial expansion of the bipolar optical lobes by Ueta *et al.* (2006) reveal that these lobes actually consist of multiple outflows at distinct inclination angles projected onto each other.

Sahai *et al.* (1998a) found that the bipolar optical lobes of the Egg Nebula are bifurcated by a dark lane that is oriented perpendicular to the symmetry axis of these lobes. This dark lane is commonly attributed to a large equatorial disk of cold dust (Sahai *et al.* 1998b; Weintraub *et al.* 2000). Observations in the continuum at 1.3mm and CO(2-1) by Cox *et al.* (2000), however, fail to detect any emission from either dust or molecular gas in the putative equatorial dust disk. In addition to the 2.122 μm H_2 emission at the outer

Figure 1. A 1.1 μm/1.6 μm image of the Egg Nebula taken with the HST/WFC3 by Balick *et al.* (2012).

tips of the bipolar optical lobes as described above, Sahai *et al.* (1998b) also discovered 2.122 μm H_2 emission on the eastern and western sides of the dark lane. Subsequent observations in CO(2-1) by Cox *et al.* (2000) showed that this H_2 emission coincides with the tips of multiple bipolar molecular outflows oriented roughly orthogonal to the bipolar optical lobes. Thus, just like the 2.122 μm H_2 emission along the bipolar optical lobes, that along the dark lane also originates from shocked gas where (multiple) bipolar outflows slam into the previously ejected AGB-star wind. The central region of the Egg nebula is therefore a source of multiple bipolar outflows along the bipolar optical lobes, as well as multiple bipolar outflows roughly orthogonal to these lobes. How such multiple bipolar outflows having essentially orthogonal orientations arise is one of the great mysteries about the Egg nebula.

In stark contrast to the strongly bipolar morphology described above, Sahai *et al.* (1998a) found a series of quasi-circular concentric arcs imprinted on the optical nebula. These arcs represent approximately equally-spaced density enhancements (by a factor of $\sim$3 over the inter-arc region) spaced in time by $\sim$100 yrs (Sahai *et al.* 1998a; Balick *et al.* 2012). Such arcs are most commonly attributed to the reflex motion of the mass-losing star (in this case, the progenitor AGB star) due to a binary companion, resulting in periodic density enhancements in the wind of the mass-losing star. The morphology and kinematics of the envelope on which the arcs are imprinted has been studied in CO(1-0) by Fong *et al.* (2006), who found the envelope to be roughly spherically symmetric and expanding at a velocity of about 14 km s^{-1}. The bipolar optical lobes are embedded in this envelope, representing features produced by the associated bipolar outflows.

Here, we present observations with ALMA that reveal the position of the source responsible for the bipolar outflows along the bipolar optical lobes. By aligning the ALMA and HST images, we address whether the source of these outflows is spatially coincident with the expansion and illumination center of the nebula. We then advance the simplest working model we can think of for the Egg Nebula: rather than to convince, our purpose is to highlight the inherent difficulties any model face for explaining both the quadrupolar outflows and arcs observed in this proto-planetary nebula. The discrepancies between model predictions and the observed features also plague other bipolar proto-planetary which are not complicated by an additional set of orthogonal bipolar outflows.

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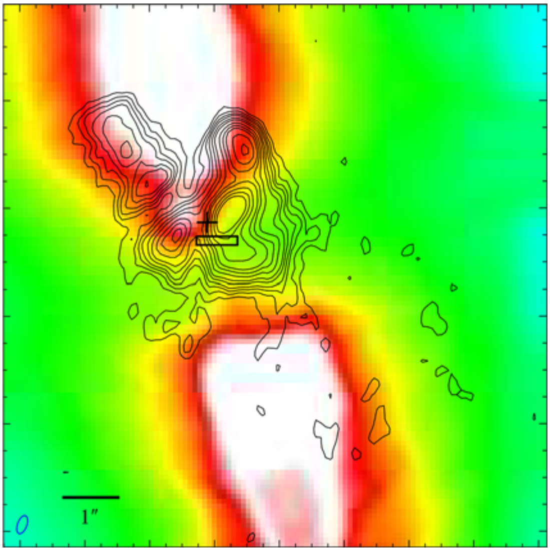

Figure 2. ALMA 1.1 mm dust continuum image (contours) superposed on the HST/WFC3 1.6 μm image (color). The cross marks the expansion center of the nebula determined by Ueta *et al.* (2006), and has arm lengths corresponding to the $\pm 1\sigma$ uncertainty of the registration between the ALMA and HST images. The rectangle indicates the illumination center as derived by Weintraub *et al.* (2000) from the linear polarization of scattered light, and has sides corresponding to their $\pm 1\sigma$ measurement uncertainties.

2. Results

Figure 2 shows an ALMA 1.1 mm dust continuum image (contours) superposed on the HST/WFC3 1.6 μm image (color). To make this overlay, we shifted the ALMA image to the epoch of the 1.6 μm image (2009 October) using the proper motion derived by Ueta *et al.* (2006) of $\alpha = (13.7 \pm 2.0)$ mas yr^{-1} and $\delta = (10.22.0)$ mas yr^{-1}. The expansion center of bipolar lobes as deduced by Ueta *et al.* (2006) is indicated by a cross, which has arm lengths corresponding to the $\pm 1\sigma$ uncertainty of our registration. The illumination center as derived by Weintraub *et al.* (2000) from the linear polarization of scattered light is indicated by a rectangle, which have sides corresponding to their $\pm 1\sigma$ measurement uncertainties. These positions of the expansion and illumination center agree to within about 2σ of the measurement uncertainties. As can be seen, the dust is concentrated in several discrete blobs, none of which coincide with either the expansion or illumination center of the nebula. Instead, the dust blobs seem to outline the base of the northern optical lobe, which is tilted towards us.

Figure 3 shows the same ALMA 1.1 mm dust continuum image (contours) but now superposed on selected ALMA HCN(3-2) channel maps (color). At the systemic velocity (middle panel), the HCN(3-2) emission coincides with the dust blobs. Evidently, both the dust and molecular gas traced in HCN(3-2) comprises material swept up and compressed by a bipolar outflow, which itself – presumably having a much higher velocity than the bipolar molecular outflows – has so-far escaped detection. The expansion center of the nebula – marking the position of the progenitor AGB star – lies precisely at the center of the molecular gas channel carved out by the bipolar outflow. At blueshifted velocities (right panel), the HCN(3-2) emission resembles a ring, as has been seen also in CO(2-1) by Cox *et al.* (2000). The expansion center of the nebula lies at or close to the center of the ring. This ring traces a spherical shell that corresponds to an episode of highly enhanced mass-loss ~200 yrs ago, presumably marking the end of the AGB phase. No ring can be

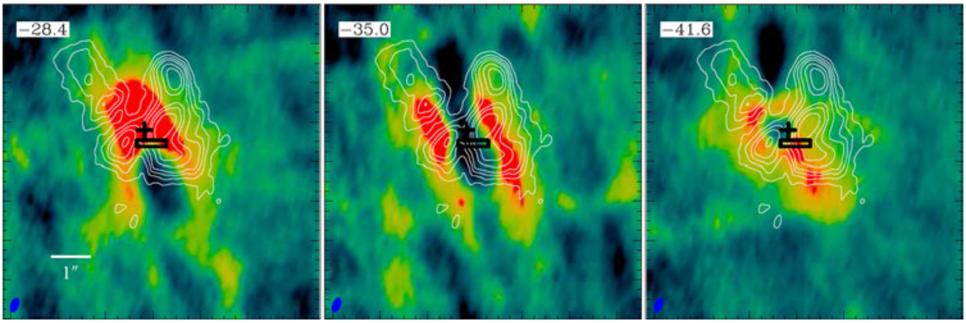

Figure 3. ALMA 1.1 mm dust continuum image (contours) now superposed on selected ALMA HCN(3-2) channel maps (color). The middle panel is at the systemic velocity of the Egg Nebula.

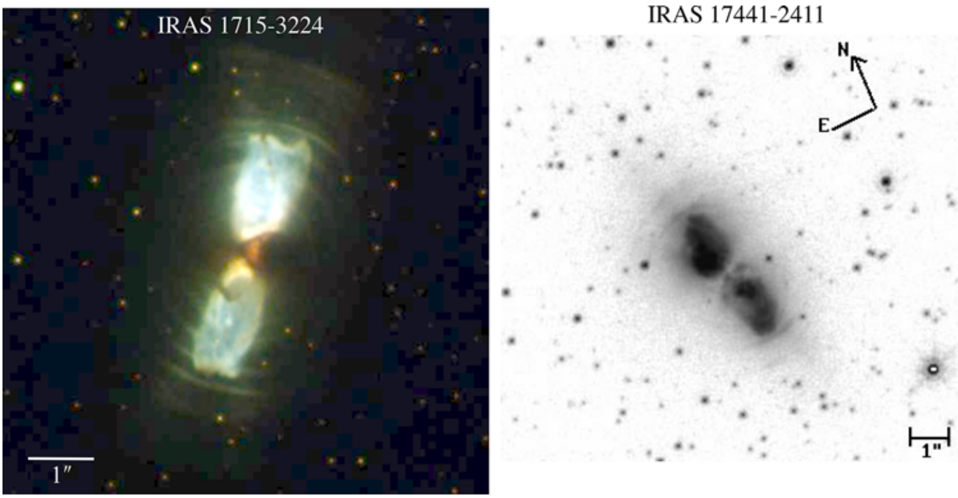

Figure 4. Optical images of two bipolar proto-planetary nebulae that also exhibit circular arcs.

seen in the images at redshifted velocities owing to blending with the swept-up emission in HCN(3-2), but this portion of the ring is clearly revealed in position-velocity diagrams (not shown here).

3. Model Challenges

Figure 3 clearly shows that the progenitor AGB star lies at or close to the source of the bipolar outflow that created the bipolar optical lobes. Sahai *et al.* (1998a) suggested that the annular cavities through which light escapes to create the searchlight beams were carved into the cocoon around the illuminating star by a precessing bipolar outflow from this star. In the picture where the arcs are caused by the reflex motion of the progenitor AGB star by a binary companion, it would be natural to attribute the bipolar outflows along the dark lane to this companion. If the axis of this outflow is perpendicular to the orbital plane, then the orbital plane of this companion would have to be approximately perpendicular to the dark lane. Theoretical models predict that arcs should be interleaved about the orbital axis and hence dark lane - no such interleaved arrangement of arcs, however, is observed along this or any other direction. To be consistent with theoretical predictions, the orbit of the binary companion would have to be in or close to the plane of the sky. If this companion is responsible for the bipolar outflows along the dark lane,

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then the circumstellar disk around this companion (from which the bipolar outflow of this star is presumably driven) would then have to be perpendicular to the orbital plane, a seemingly unnatural configuration if the material comprising the circumstellar disk of this star was captured from the progenitor AGB star.

A similar problem plagues this model as applied to other bipolar proto-planetary nebulae, but which do not have the complexity of an additional set of bipolar outflows perpendicular to the bipolar optical lobes. In Fig. 4, we show two examples, both of which have clear circular arcs. Once again, for a binary companion to produce these arcs, the orbital plane of the companion would have to be in or close to the plane of the sky, whereas the circumtellar disk from which the outflow originates to produce the bipolar lobes would have to be oriented in a perpendicular direction.

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Discussion

D'Antona: I wonder whether your presumed binary companion of $0.2\,M_{\odot}$ with a wide separation would mean that there are different paths to the asymmetric PN, one involving common envelope evolution and the other one avoiding it?

Lim: In my talk, I considered the possibility of a close binary companion driving the bipolar outflows that carved out the bipolar optical lobes, and another more distant companion to drive the bipolar outflows that coincide with the dark lane - one of the many models we considered to come up with a coherent picture for all the features observed in the Egg Nebula. Of course, this model does not exclude common envelope evolution, that is between the AGB star and its nearby binary companion.

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