

## THE ORIGIN OF ASYMMETRY IN PROTO-PLANETARY NEBULAE

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## ABSTRACT

The transition from Asymptotic Giant Branch (AGB) star to Planetary Nebula is a short lived and mysterious evolutionary phase for intermediate-mass stars. Though it lasts only a few thousand years, it is thought to be the time when the asymmetries observed in subsequent phases arise. However, there are very few that we have caught in the act; those that have been identified are shrouded in thick clouds of dust and molecular gas. Thus, infrared observations are needed to reveal these objects at their most pivotal moment. I present preliminary results of an observational program carried out using the infrared *Spitzer Space Telescope* on targets spanning the range from post-AGB stars to young Planetary Nebulae with the goal of determining the genesis of asymmetry in these objects.

## 1. INTRODUCTION

1.1. *Stellar Evolution*

The trajectory of a star's lifetime and the manner of its ultimate demise depends on the star's mass. While high-mass stars, roughly those with more than eight solar masses, end their lives explosively as supernovae, low-mass stars with less than half a solar mass just fizzle and cool. Intermediate-mass stars, such as our sun, eventually fling their outer layers into space, forming planetary nebulae.

1.2. *The Proto-Planetary Nebula Phase*

The focus of this research is the late stages of the life cycle of intermediate mass stars. These stars spend the majority of their lifetimes on the Main Sequence, fusing Hydrogen into Helium in their cores like our Sun. The Hydrogen will eventually run out. They leave the main sequence and begin to fuse Helium and expand, becoming Giant stars. Eventually, the core Helium will run out as well. The star will instead start to burn nuclear fuel in shells surrounding the spent core. This type of fusion is far less stable and can lead to pulsations in the star called thermal pulses. These pulsations send a blast of energy out from the star which carries away material from the outer layers (Habing & Olofsson 2003). These violent pulsations mark what astronomers call the "Asymptotic Giant Branch" (AGB) phase. During this stage, there is a slow, steady and spherically symmetric stream of material leaving the star called the AGB wind. This wind is interspersed with shells of enhanced density due to pulsation. These shells have been observed in Planetary Nebulae such as the Cat's Eye Nebula seen in Figure 1 (Balick et al., 2001). As this material expands and escapes into space, it carries the imprint of the star's turbulent past.

As the mass loss process continues, the thick cloud of dust and gas it creates begins to obscure the star itself (García-Lario, 2006). Though we can conjecture about what happens next, we have precious little observational evidence for it. What we do know is that when the star emerges just a short time later, it is suddenly the central star of a spectacular, and often highly asymmetric, Planetary Nebulae. Somehow, during this phase of mere



FIG. 1.— An Optical/Near Infrared image of The Cat's Eye Planetary Nebula taken with the *Hubble Space Telescope*. Clearly visible are shells associated with short periods of enhanced mass loss, thought to be a result of semi-regular pulsations spaced 1,500 years apart. Image credit: R. Corradi, Z. Tsvetanov, Hubble WFPC2, NASA, ESA, and STScI/AURA

thousands of years, the structure of the winds, and perhaps the star itself, change fundamentally. So what happens behind that great cloud of dust and gas? An answer to this unsolved mystery is the aim of this investigation.

The star itself is invisible at all wavelengths during the transition (called the post-AGB and Proto-Planetary Nebula (PPN) phase), but we do have some indirect clues to the interior process. In some cases, light from the central star is reflected by the surrounding dust and gas, as in the case of the Red Rectangle seen in Figure 2 (Cohen et al., 2001) and The Egg Nebula (Figure 3, Sahai et al. 1998), though these tend to be very evolved objects that are nearing Planetary Nebula status. In PPN of all ages, the central star is heating the surrounding dust and



FIG. 2.— An Optical/Near Infrared image of Proto-Planetary Nebula HD 44179, called The Red Rectangle, taken with the *Hubble Space Telescope*. The central binary star is obscured by a dusty lane thought to be a circumstellar torus viewed edge-on. Image credit: Hubble WFPC2, NASA, ESA, H. VanWinckel and M. Cohen

gas, which causes it to emit light in the infrared. Near-infrared light travels from the hot innermost regions of the stellar envelope through the cold, dusty outer layers where optical light is blocked, while longer wavelengths reach us from the warm interior of the dust cloud itself. Thus, infrared observations allow us to peer inside the dusty cocoon during this pivotal phase.

Theory provides us with some idea of what we can expect to find. The dust-enshrouded star will contract and heat up as it continues to burn (Kwok, 1993). Eventually, it will become hot enough to start emitting UV photons, which carry enough energy to excite and eventually ionize the gas around it. When this process begins, there will be an ionization front (sometimes accompanied by a shock) that travels outward through the gas cloud, ultimately evaporating the dust or pushing it away. This concludes with the star re-emerging as the central star of a planetary nebula. It is also possible that the hot star creates a tenuous fast wind of its own, which could theoretically slam into the slow AGB wind and create a shock front.

So what exactly can these observations reveal? Spectra tell the chemical story of the dust cloud: what sort of molecules have formed, how those molecules are being excited, how warm they are, and how the light from the central star is ionizing them. Images tell the story of geometry: where the gas has been ionized, where the gas is being shocked, how far into the cloud the stellar light is reaching, and how the temperature of the dust varies across the cloud (Glassgold, 1996). Together, these observations promise to tell the story of how asymmetries form and manifest themselves in the shaping of a future planetary nebula.

## 2. THE SAMPLE

A sample of targets was chosen to span the entire temporal sequence from star to nebula. This sequence was divided into three constituent epochs: post-AGB stars, true Transition Objects (Proto-Planetary Nebulae), and

Planetary Nebulae. Each of these epochs were the subject of an observational program using the *Spitzer Space Telescope*.

### 2.1. Post-AGB Stars and Proto-Planetary Nebulae

These objects are not well-defined observationally since so little is known about the transition process. As a proxy, our sample was chosen on the basis of Spectral Energy Distributions, specifically those that show anomalous excess emission in the far infrared. This excess is a signature of large quantities of circumstellar dust, which is a distinguishing feature of this evolutionary phase (García-Lario, 2006). Where the spectrum of the star itself was available, stars of spectral type B were selected, since these should be hot enough to have begun to ionize their circumstellar envelopes.

### 2.2. Planetary Nebulae

The Planetary Nebula program was focused on a subtype of planetary nebulae known to have a "dual-dust chemistry" (Cohen et al 1999, 2002). These objects straddle a critical boundary in phase space that makes them particularly important for studies of the transition epoch.

Typically, an evolved post-AGB star falls into one of two categories: Carbon-rich or Oxygen-rich. This designation refers to the nature of the dust created in their winds. Due to the high binding energy of CO, this molecule will form first, leaving behind only carbon or oxygen to form other compounds, depending on which there was more of. All AGB stars start in the oxygen-rich category, and thus display spectral signatures associated with oxygen-based crystalline silicates and water ice. These stars undergo a "dredge up" process, where carbon is carried up to the surface of the star in huge convection cells. Only a select few experience a "dredge up" process that is efficient enough to overwhelm the oxygen (Glassgold, 1996). Any oxygen that comes in contact with that carbon will form CO, which will tie up all of the atmospheric oxygen. These stars have spectral signatures associated with a variety of carbon-based Polycyclic Aromatic Hydrocarbons.

In a small minority of cases, we observe spectral evidence for both carbon-based and oxygen-based dust (Pe. This can only be the case if the two types of dust are spatially isolated from one another. The most popular theory is that the O-rich dust is preserved in a circumstellar disk and is thus shielded from the influx of carbon. These objects serve the same purpose as a broken stop-watch at the scene of a crime: we know that the dust chemistry change, which is associated with a very specific evolutionary sequence, happened after the formation of the disk.

This could be the pivotal clue necessary to string together an evolutionary sequence out of the observational sample. What makes them additionally useful is that the two different structures are easily distinguished on the basis of their chemistry. For this reason, even in spectra that are unresolved, we can study the properties of the disk in isolation from the lobes and vice versa. The same is true for narrow-band imaging: a strategic choice of wavelength range can isolate one structure or the other. These images can inform us about the age and evolutionary status of the individual components.

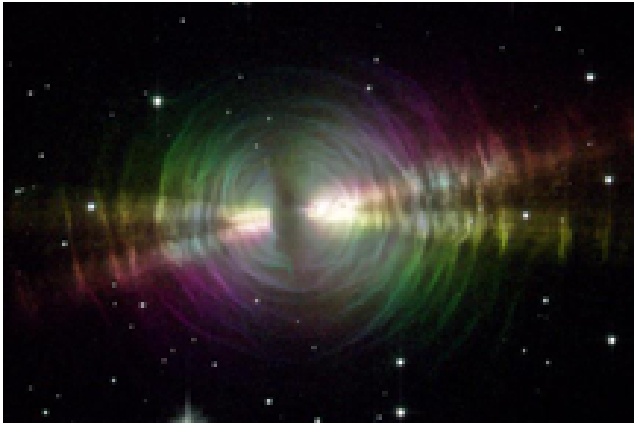


FIG. 3.— An Optical/Near Infrared image of a Proto-Planetary NGC 1705, named the Egg Nebula, taken with the *Hubble Space Telescope*. The central star is obscured by the dust cloud, but the shells are illuminated in reflected light. Beams of light appear to be breaking through at the poles of the dusty cloud, a common feature in these objects. Image credit: NASA and The Hubble Heritage Team (STScI/AURA) W. Sparks (STScI) and R. Sahai (JPL)

### 3. OBSERVATIONS

#### 3.1. Completed

The three programs that were taken with the *Spitzer Space Telescope* (Werner et al. 2004) that form the basis of this project were completed in 2009. The sample comprises about 75 targets in total, all with infrared spectra covering 5–40  $\mu\text{m}$  measured on the Infrared Spectrograph (IRS) (Houck et al. 2004) and also observed with the Infrared Array Camera (IRAC) imager (Fazio et al. 2004), which images each object in four broadband channels centered at 3.6, 4.5, 5.8, and 8.0  $\mu\text{m}$ .

Additionally, several nights have been awarded for use on the 6.5 meter Magellan telescope (Sectman & Johns, 2003) with the MMIRS Near-Infrared Spectrograph (McLeod et al. , 2004) to observe the objects in the *Spitzer* sample that are observable from the southern hemisphere. These observations were completed in early April 2010. As of the date of this publication, only a sample of raw the data has been received.

#### 3.2. Planned

Observing time has also been awarded to image the subset of sources in the *Spitzer* sample that have extended emission using Near Infrared narrowband filters that isolate specific emission lines with PANIC (Martini et al. 2004) on Magellan. That observing run is scheduled for the end of April 2010, and I will travel to the Las Campanas Observatory in Chile to take the data myself.

### 4. DISCUSSION

The IRS spectra were extracted using SMART (Spectroscopic Modeling Analysis and Reduction Tool), an IDL-based package that was developed by the IRS team at Cornell University (Lebouteiller et al. 2010; Higdon et al. 2004). An AOR-averaged background was subtracted from each raw BCD image, then coadded with matching images in the same BCD. The spectra were then extracted using the Optimal Point-Source extraction. Next, the spectral orders were clipped to the published, scientifically valid wavelength ranges and then combined. Analysis of these spectra is underway; model fits will be used to place the array of spectra in an evolutionary sequence. The IRAC data has yet to be reduced, along with the incoming data from the Magellan telescopes which has yet to be delivered.

### 5. ACKNOWLEDGEMENTS

This work is based (in part) on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407. Support for the IRAC instrument was provided by NASA under contract number 1256790 issued by JPL. This research also has made use of the SIMBAD database, operated at CDS, Strasbourg, France and NASA's Astrophysics Data System Bibliographic Service. I would also like to thank the Rocky Mountain NASA Space Grant Consortium and Smithsonian Astrophysical Observatory for their generous support of this research.

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