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# Resolving the Multiple Outflows in the Egg Nebula with Keck II Laser Guide Star Adaptive Optics

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**Summary.** The Egg Nebula has been regarded as the archetype of bipolar protoplanetary nebulae, yet we lack a coherent model that can explain the morphology and kinematics of the nebular and dusty components observed at high-spatial and spectral resolution. Here, we report on two sets of observations obtained with the Keck Adaptive Optics Laser Guide Star: H to M-band NIRC2 imaging, and narrow bandpath K-band OSIRIS 3-D imaging-spectroscopy (through the H<sub>2</sub> 2.121 $\mu$ m emission line). While the central star or engine remains un-detected at all bands, we clearly resolve the dusty components in the central region and confirm that peak A is not a companion star. The spatially-resolved spectral analysis provide kinematic information of the H<sub>2</sub> emission regions in the eastern and central parts of the nebula and show projected velocities for the H<sub>2</sub> emission higher than 100km s<sup>-1</sup>. We discuss these observations against a possible formation scenario for the nebular components.

**Key words:** CRL 2688, post-AGB, PPN, Adaptive Optics

## 1 Introduction

The Egg Nebula is a prototypical bipolar pre-planetary nebula (PPN): in the optical, the direct light from the central star is obscured by dust, while two lobes aligned along a “polar axis” scatter the starlight towards the observer [1]. Yet, at longer wavelengths, the Egg Nebula reveals a more complex geometry: multiple CO outflows in the equatorial plane and at higher latitude [2]; dusty knots (peak A) and a dark lane at a PA=140° [3]; and H<sub>2</sub> (2.12 $\mu$ m) emission line spatially coincident with the obscuring dust in the equatorial plane [4]. The models presented in [5] or [3] don't explain some of these features such as the existence of the multiple outflows. We present some of the near-infrared imaging and imaging-spectroscopy results at high spatial ( $\leq 0.1''$ ) and spectral ( $\approx 60\text{km s}^{-1}$ ) resolution from the Egg Nebula obtained with the Keck II Laser Guide Star Adaptive Optics (LGS-AO) System. These LGS-AO images of the central regions show details on the dusty knots and the H<sub>2</sub>

emission with un-precedent spatial resolution. Combined with ACS/HST F606W images and LGS-AO 3-D imaging spectroscopy through the H<sub>2</sub> line, we analyze the detailed structure of the outflows for the eastern part of the nebula. We tentatively propose that multiple highly collimated outflows, launched by intermittent and precessing mechanism could explain the Egg morphology. A paper describing the full NIRC2 imaging data set, compared to visible HST ACS and including an analysis of the 3-D imaging spectroscopy over all outflows is in preparation [6].

## 2 NIRC2 imaging and OSIRIS imaging-spectroscopy

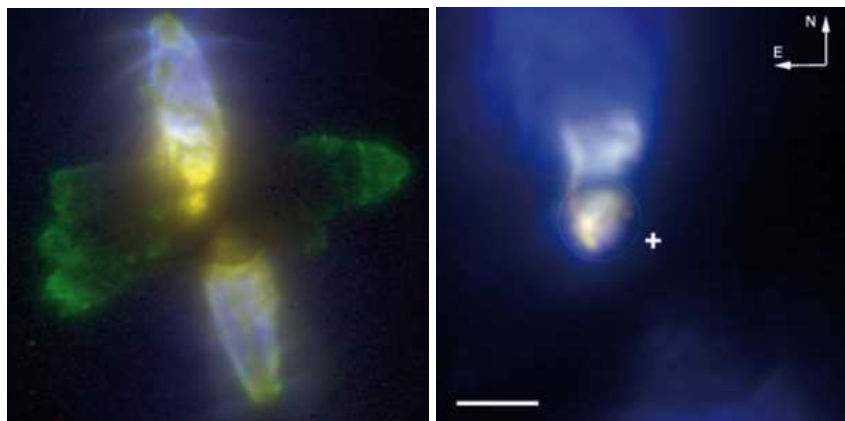
In July 2004, we used the AO-dedicated near infrared camera NIRC2 behind the Keck II Laser Guide Star (LGS) Adaptive Optics (AO) system [8], [9], to record broad-band and narrow-band images. Earlier LGS-AO observations of the Egg were reported in [7] and suffered from variable image quality. Later in 2006, we were allocated Director's Keck II LGS time for imaging spectroscopy of the Eastern and Center regions of the CRL2688 using OSIRIS, the AO-dedicated Integral Field Unit [10]. Table 1 summarizes the observations presented here.

**Table 1.** Keck LGS-AO observations of the Egg Nebula reported in this work

Region	Instrument	Spatial sampling	Filter	$\lambda_0$	$\Delta_\lambda$
5'' $\times$ 5'' centered	NIRC2	0.''01/pix	Lp	3.78	0.70
5'' $\times$ 5'' centered	NIRC2	0.''01/pix	Ms	4.67	0.24
10'' $\times$ 10'' centered	NIRC2	0.''01/pix	Kp	2.12	0.35
40'' $\times$ 40'' centered	NIRC2	0.''04/pix	H <sub>2</sub> $\nu=1-0$	2.121	0.034
40'' $\times$ 40'' centered	NIRC2	0.''04/pix	Kcont	2.270	0.030
4'' $\times$ 6'' centered	OSIRIS	0.''1/lenslet	Kn2	2.089	0.105
4'' $\times$ 6'' on east	OSIRIS	0.''1/lenslet	Kn2	2.088	0.105

### 2.1 Results from NIRC2 Imaging

A spatial resolution of 70 milli-arcsec was estimated from the NIRC2 wide-camera images. All NIRC2 wide camera images were registered against archived ACS WFC1 F606W observations from October 2002 (data set j8gh55010, P.I. R. Sahai) Fig. 1 displays a color-combined NIRC2 and HST image and a color-combined NIRC2 image (see caption). There are a few noticeable features: 1) the visible (blue) light is primarily scattered inside the two N and S lobes and along the two searchlight beams [1]; the scattered light in the K cont., Lp and Ms band is also seen along the N and S lobes and closer to the central hidden star. Except for the N/S lobes, the only other location where scattered light is seen in the NIR is around peak A [11]; there is no detection of K, Lp or Ms continuum emission in the equatorial region, indicating a total absence of continuum scattered light in this region; 2) the H<sub>2</sub> emission regions appear as dense knots, filaments and arcs spatially coincident with the edges of the obscuring/scattering dust knots seen along the N/S lobes, at the tips



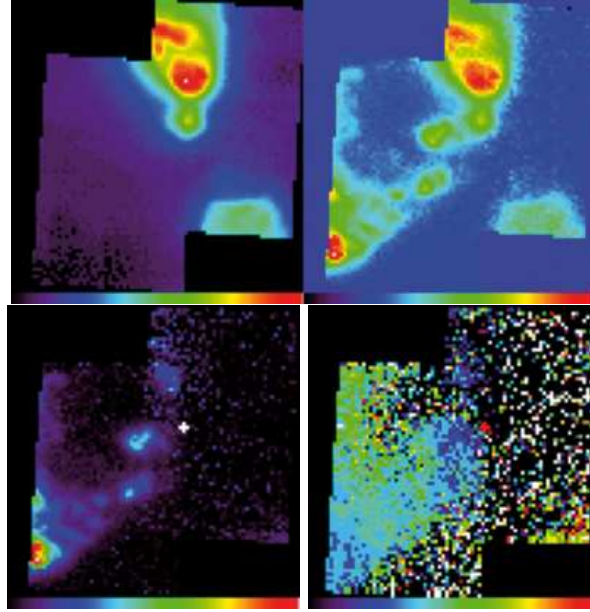
**Fig. 1.** **Left:**  $20'' \times 20''$  false-color image consisting of ACS F606W POL-0 (blue), NIRC2 H<sub>2</sub> (green) and NIRC2 Kcont (red) images. **Right**  $5'' \times 5''$  false-color NIRC2 image of the central region using Kp-band (blue), Lp-band (green) and Ms-band (red) images; The display intensity scale is  $I^{0.25}$ . The scale bar is  $1''$ . The cross marks the central star location, and a light circle surrounds peak A.

of the outflows in the equatorial region, and at the tips of the mid-latitude multiple outflows, some of them, G<sub>1</sub>, E<sub>1</sub>, D<sub>1</sub>, reported in the lower resolution CO maps from [2]; 3) the 2004 Lp and Ms images show that peak A is now well-resolved into a  $0.''5$  dusty knot with a complex structure, possibly indicative of a nascent outflow in the direction towards the observer; in the same image, there is a unresolved wiggling filamentary structure bridging from the N lobe onto peak A that could be indicative of highly-collimated processes (e.g., a precessing jet) in the vicinity of the central engine.

## 2.2 Results from OSIRIS Imaging Spectroscopy

Two regions in the Egg nebula were observed using OSIRIS: one centered on the central star, the second one centered on the East H<sub>2</sub> emission region. The lenslet choice of  $0.''1$  (in order to cover  $4'' \times 6''$  area at once) defines our spatial resolution. The data was reduced using the OSIRIS Data Reduction Pipeline. Fig. 2 (upper row) shows a mosaic of the two regions observed, as the average over the cube or over the H<sub>2</sub> ( $2.12\mu\text{m}$ ) line. A 421-channel spectrum for each  $0.''1 \times 0.''1$  spaxel over the  $2.036\text{--}2.141\mu\text{m}$  range was extracted and corrected for telluric absorption. The emission features include H<sub>2</sub> S(1) (1,0) ( $2.1218\mu\text{m}$ ), H<sub>2</sub>- S(3) (2,1) ( $2.073\mu\text{m}$ ) and HeI ( $2.1298\mu\text{m}$ ) whereas the He I 4s 3S-3p 3P0 ( $2.1133\mu\text{m}$ ) is detected in absorption. A spectral resolution of  $60 \text{ km s}^{-1}$  has been measured on the unresolved telluric OH lines. For each spaxel, we fit a continuum and a gaussian profile through the H<sub>2</sub> emission line and extracted relative integrated intensity, velocity dispersion and line peak centroid.

The map of continuum-subtracted H<sub>2</sub> flux (see Fig. 2 bottom left) shows that the H<sub>2</sub> emission is not uniformly distributed over the observed region, but rather appears as 4 to 6 clumpy knots of angular size of  $\approx 1''$  or less, roughly aligned along an arc



**Fig. 2.** **Upper row** The left mosaic image corresponds to the average over the 421 spectral channels, therefore dominated by scattered light, while the right mosaic image is the average over the H<sub>2</sub> line (no continuum has been subtracted). The image intensity scale is  $I^{0.25}$ . **Bottom left** Map of the continuum-subtracted integrated flux for the shocked H<sub>2</sub> emission line (using linear intensity scale). **Bottom right** Map of the H<sub>2</sub> line peak centroid shift in  $\text{km s}^{-1}$  (using linear intensity scale). The velocity shift covers a range of  $100 \text{ km s}^{-1}$ . – Each mosaic image is  $8'' \times 8''$  with  $0.''1$  spatial resolution.

joining the East lobe to the N lobe. None of these clumps is superimposed with peak A location.

The shift in peak centroid is displayed on the right-most image. We measure a velocity shift amplitude for this part of the nebula of  $100 \text{ km s}^{-1}$ , a factor 2 higher than previous work [12]. The highest projected velocities are found near (but not at) peak A, at smaller spatial scales ( $\leq 0.''3$ ) which could not be probed in earlier studies. The high-velocity outflows north of the central star (cross) coincide with the clumpy H<sub>2</sub> knots closer to the N lobe and could be associated with a precessing jet, suggested in 2.1.

### 3 Discussion and conclusion

From the preliminary analysis of our data sets, we conclude 1) the absence of continuum light in most outflows, 2) a distribution of H<sub>2</sub> emission coincident with dense, dusty clumps, 3) a possible nascent outflow at the peak A location, and 4) the existence of fast highly-collimated outflows, possibly jets. We stress that any qualitative model must account for the non-detection of continuum light in the equatorial

outflows, in contrast to the polar ones. The continuum light from the central star must be heavily obscured either in the equatorial outflow cavity or before it reaches the cavity. We speculate a possible shaping mechanism that could account for these observables: the central engine of the Egg is heavily obscured by a cocoon of dust and intermittent jet-like outflows may be launched by MHD mechanisms within the vicinity of the central engine [13]. An outflow would break through the dust cocoon, heating and dissipating the surrounding dust and expands for a few hundreds of years [14]. The continuum starlight would propagate through the cavity and be scattered. H<sub>2</sub> shocked emission would be detected primarily at the tip of the outflow. Eventually, the continuum starlight becomes heavily obscured by dust again. In addition, new outflows would be launched rapidly and account for the multiple outflows with comparable dynamical age [2]. The outflows where only H<sub>2</sub> shocked emission is detected would correspond to past outflows.

We are currently completing LGS high-spatial imaging spectroscopy over the entire nebula to further constrain the kinematics and discuss the possible launch mechanism for the outflows.

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