PROCEEDINGS OF SCIENCE

Differential Proper-Motion Measurements of the Cygnus Egg Nebula; The Presence of Equatorial Outflows

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We present the results of differential proper-motion analyses of the Egg Nebula (RAFGL 2688, V1610 Cyg) based on the archived two-epoch optical data taken with the Hubble Space Telescope. First, we determined that the polarization characteristics of the Egg Nebula are influenced by the higher optical depth of the central regions of the nebula (i.e., the "dustsphere" of about 103 AU radius), causing the nebula to illuminate in two steps-the direct starlight is first channeled into bipolar cavities and then scattered off to the rest of the nebula. We then measured the amount of motion of local structures and the signature concentric arcs by determining their relative shifts over the 7.25 yr interval. Based on our analysis, which does not rely on the single-scattering assumption, we concluded that the lobes have been excavated by a linear expansion along the bipolar axis for the past $\sim$400 yr, while the concentric arcs have been generated continuously and moving out radially at about 10 km s^{-1} for the past $\sim$5500 yr, and there appears to be a colatitudinally increasing trend in the radial expansion velocity field of the concentric arcs. Numerical investigations into the mass-loss modulation by the central binary system exist, which predict such a colatitudinally increasing expansion velocity field in the spiral-shock trails of the mass-loss ejecta. Therefore, the Egg Nebula may represent a rare edge-on case of the binary-modulated circumstellar environs, corroborating the previous theoretical predictions in more general context.

The Life Cycle of Dust in the Universe: Observations, Theory, and Laboratory Experiments - LCDU 2013,
18-22 November 2013
Taipei, Taiwan

PoS(LCDU 2013)147

1. Introduction: the Egg Nebula and the Enigma of its Shell Structures

The Cygnus Egg Nebula is one of the first infrared sources ever discovered with an optical reflection bipolar nebulosity [1]. This object consists of the central star in the post-AGB phase of evolution and the circumstellar envelope that resulted from mass-loss processes during the preceding AGB phase. One of the most peculiar characteristics of the circumstellar shell structure of the Egg Nebula is the co-presence of the nebula's signature bipolar lobes and rather circular concentric arcs superposed on top of each other [2]. These concentric arcs are qualitatively perceived as some manifestations of spherically symmetric mass-loss processes that took place in early AGB mass-loss phases. However, the deduced temporal intervals do not match with any of the known theoretical temporal intervals that have been proposed so far [3]. A differential proper-motion analysis is a direct way to measure the amount of motion and will help to understand the dynamics of the circumstellar structure formation.

2. Differential Proper-Motion Measurements of the Egg Nebula

Optical imaging polarimetric maps of the Egg Nebula show more prominent circumstellar structures in the total intensity image than the polarized intensity image. This suggests that the strength of the polarized intensity is marginalized due to multiple scattering in a relatively optically thick circumstellar nebula of the object. Thus we employ a set of two-epoch total intensity images to follow the differential proper motion of local shell structures. Briefly, this method measures the amount of translational shift of a given structure between two epochs via a cross-correlation analysis [4]. For the present analysis 30 distinct local structures are selected.

The results of the cross-correlational analysis are summarized in Figure 1 as a projection map of differential proper-motion vectors and a plot of the radial component of the projected differential proper-motion vector ($v_{\rm rad}$ in mas yr^{-1} and km s^{-1}) versus projected radial distance R from the center. The present analysis clearly shows that the arc segments in the "searchlight beams" beyond the lobes move at roughly a constant expansion speed of $v_{\rm rad} = 10.52 \pm 0.34$ km s^{-1} (assuming the 420 pc distance; the solid black line in the light-gray zone in Figure 3b), while the arcs overlapping with the lobes follow a linear expansion at $(5.10 \pm 0.33) \times R$ km s^{-1} (the solid white line in the dark-gray zone). Also indicated are the dynamic ages of these components: at least 5,500 yr for the arc segments in the searchlight beams and 390 yr for the lobes.

To measure the projected radial motion of arcs closer to the equatorial plane, the two-epoch images are projected into the polar coordinates (Figure 4a,b) and the radial velocity is measured for each 1° segment (Figure 4c). While uncertainties are relatively large owing to a large S/N discrepancy between the two-epoch maps, the present data suggest that the projected radial velocities tend to (1) converge to a minimum of about 10 km s^{-1} toward the regions of the searchlight beams/bipolar axis, and (2) increase by a factor of about a few moving toward the equatorial plane.

Combined altogether, it appears that there are three distinct outflow components in the circumstellar environs of the Egg Nebula. The concentric arcs are most likely manifestations of periodical modulations taking place in a generally spherically symmetric steady outflow at 10 km s^{-1}. This symmetric structure seems to be disrupted by two other distinct outflow components, one along the bipolar axis and the other along the equatorial plane. The bipolar lobes have been being excavated

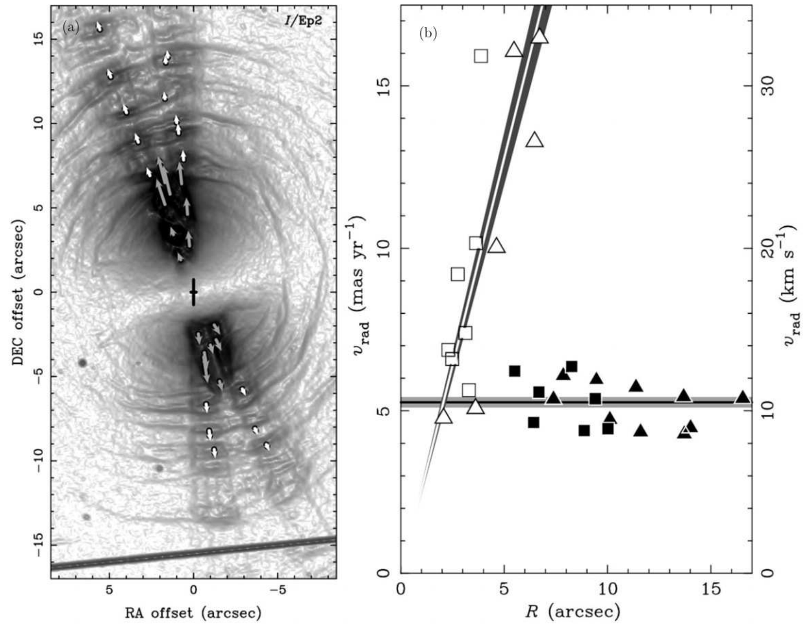

Figure 1: (a) The edge-enhanced epoch-2 total intensity map of the Egg Nebula overlaid with differential proper-motion vectors of the projected radial component of the shell expansion: gray vectors are of the lobes, while white vectors are of the arc segments. (b) The plot of v_{rad} vs. R. The symbols indicate lobe structures (open triangle-north lobe; open square-south lobe) and arc segments (filled triangle-north arcs; filled square-south arcs). The best-fits are shown as the white solid line with the gray uncertainty (lobes) and black solid line with the light gray uncertainty (arc segments).

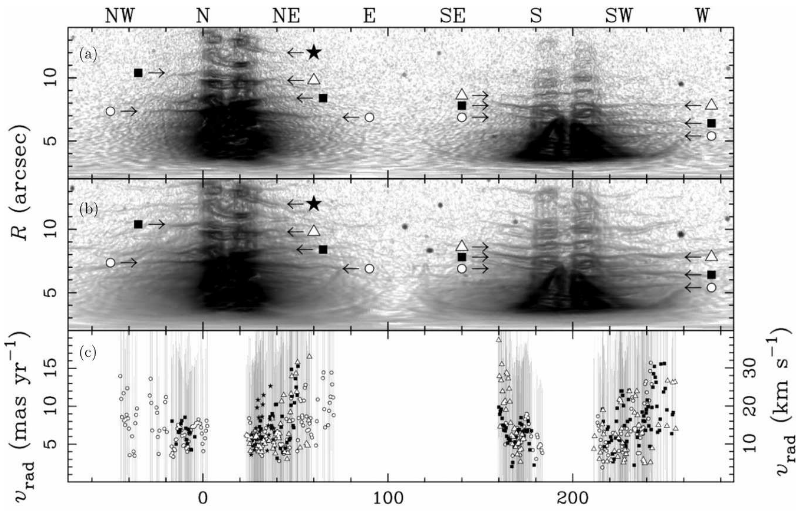

Figure 2: The edge-enhanced total intensity polar maps of the Egg Nebula for epoch 1 (top) and epoch 2 (middle), with the distribution of measured projected $v_{\rm rad}$ in the 12 most prominent arcs showing the apparent increasing trending of the radial velocity toward the equatorial plane (bottom). The polar angle is the position angle measured from north to east, with the orientations indicated above the top frame. Each symbol in the bottom frame represents a differential radial-motion measurement for each 1° arc segment as a function of the position angle. Uncertainties of the radial velocity measurements are indicated by the vertical lines attached to each symbol.

by a linear expansion for the past $300-400$ yr with the tip velocity about $30\,\mathrm{km\,s^{-1}}$ [4]. The outflow component along the equatorial plane appears to increase latitudinally up to $20-30\,\mathrm{km\,s^{-1}}$ based on the ways that concentric arcs are being disrupted, lending support for an edge-on binary system in which (1) the spiraling trails of mass-loss ejecta appear as concentric arcs, and (2) the colatitudinal velocity field promotes an equatorial outflow fast enough to disrupt the ejecta [5, 6].

3. Summary

We performed differential proper-motion and radial-motion analyses on both the signature bipolar lobes and concentric arcs of the Egg Nebula using two-epoch optical data taken by the HST. Details of the analysis is found elsewhere [7]. Our method, based on (1) aligning two-epoch images using stationary background stars as spatial anchors, and (2) measuring the amount of translational movement of specific local structures by a correlational method, found that;
(1) The Egg Nebula is optically illuminated by a two-step mechanism, in which the direct starlight is first channeled into the bipolar cavities and then scattered off to the rest of the nebula;
(2) There is a "dust sphere" around the central star (1.0×10^3 AU by 1.6×10^3 AU at 420 pc), most likely representing the surface of the central dust concentration at which the line-of-sight optical depth in the V band becomes significantly larger than unity;
(3) The bipolar lobes expanded linearly for the past 390 ± 25 yr, excavating into an otherwise symmetric concentric shell as found by our previous analysis;
(4) Arc segments found along the searchlight beams beyond the bipolar lobes all move at similar projected radial velocity at $10.52\pm0.34\,\mathrm{km\,s^{-1}}$ for the past 5,500 yr;
(5) The projected radial expansion velocity field of the concentric arcs shows an increasing trending toward the equatorial plane by a factor of a few, representing torn-off edges of the arcs disrupted by a fast equatorial outflow at $>20-30\,\mathrm{km\,s^{-1}}$;
(6) The present case may provide observational evidence for the binary modulation of stellar winds, which generate the colatitudinal dependence in the radial expansion velocity field and the spiral shocks of the mass-loss ejecta appearing as concentric arcs in near edge-on orientations.

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