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Investigating proto-planetary nebulae through angular differential imaging

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Studying the Proto-Planetary Nebula (PPN) stage of a star's life sheds light on the critical mass-loss mechanism that leads to the morphological change from spherically symmetric to axisymmetric circumstellar material. However, when studying material very faint in reflection so close to a star, the brightness of the star itself becomes prohibitive. Therefore, in order to study the circumstellar material more effectively, it is necessary to block out the central star. The method of angular differential imaging (ADI), used in this research, takes advantage of altitude-azimuth telescopes by turning off the telescope rotator and allowing a series of images to be taken that are slightly rotated with respect to each other. This creates a better characterization of the point-spread-function (PSF) of the central star for more effective subtraction than previous PSF subtraction techniques. ADI has successfully been used to verify extrasolar planets, but this is one of the first attempts at adopting ADI techniques for extended structures as opposed to point sources. In this study, ADI techniques were applied to PPN observations to better study the most recent mass-loss histories of PPNs. Data for the PPNs were taken at the Near Infrared Coronographic Imager (NICI) at Gemini South between March and September 2012. Due to the low contrast of the objects studied, this research truly pushes the boundaries of ADI methods. New details on the circumstellar structure of 6 PPNs are presented.

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1. Background information

Proto-planetary nebulae (PPNs) are stars of intermediate initial mass (0.8 – 8 $M_\odot$) between the asymptotic giant branch phase and the planetary nebula phase of stellar evolution [1, 2]. They evolve over a very short time period (roughly 10^3 yrs), and hence, tend to be rare in the sky. Studying the PPN stage of a star's life sheds light on the critical mass-loss mechanism that leads to the morphological change from spherically symmetric to axisymmetric distribution of the circumstellar material. However, when studying distributions of such circumstellar material very faint in reflection so close to the central star, the sheer brightness of the star itself becomes prohibitive.

Therefore, in order to study the circumstellar material more effectively, it is necessary to block out the central star. We have used in the past one such method, known as imaging polarimetry, to isolate the dust-scattered linearly-polarized star light reflected off the circumstellar shell from the unpolarized star light directly received from the central star [3, 4]. Here, we report our recent use of another method, called the angular differential imaging (ADI), using the Near Infrared Coronographic Imager (NICI) at Gemini-South to suppress the emission from the central star.

2. Angular differential imaging

The method of ADI takes advantage of the principle of altitude-azimuth telescopes by turning off the image rotator to allow the sky to rotate with respect to the instrument frame of reference in a series of images to be taken. This allows a better characterization of the point-spread-function (PSF) of the central star, because the PSF structure is fixed to the instrument frame of reference, while any other structures intrinsic to the target object are fixed to the sky frame of reference. Hence, the straight median of a series of exposures results in a PSF image, which can then be subtracted from each exposure. De-rotating each PSF-subtracted image by its parallactic angle and taking a median of these images produces a final image that ideally shows just the distribution of material surrounding the star [5].

While ADI has been devised and successfully been used to discover extra-solar planets (i.e., fainter point sources around the bright central star; [7, 8, 9, 10, 11]), this is one of the first attempts in adopting ADI for extended structures as opposed to point sources. In this study, ADI techniques are applied to PPN observations to better study the most recent mass-loss histories of PPNs.

3. Data and methods

Data for this study were taken with NICI at Gemini-South between March and September 2012. While data were obtained for 12 PPNs, some of the target PPNs were not observed for a long enough duration for the ADI method to work (i.e., not enough sky rotation) due to adverse weather conditions. As a result, PSF subtraction was performed for only 6 PPN candidates: HD 179821, IRAS 08143-4406, IRAS 07134+1005, IRAS 08005-2356, IRAS 11385-5517, and IRAS 12175-5338.

We reduced the data sets using the custom reduction codes provided by Nelson Zarate [6] and Neil Zimmerman [7]. These codes are based on ADI-specific image reconstruction algorithms known as the Locally Optimized Combination of Images algorithm (LOCI; [8]), and the Karhunen-Loéve Image Projection algorithm (KLIP; [9]), respectively. These algorithms are based on the premise that the detector pixels scan the sky most of the time and occasionally come across parts of the target object(s) in question (i.e., companion point sources), so that the sky emission can be recovered from the median of time-series exposures for all the detector pixels.

Note, however, that our target sources are (expected to be) associated with a circumstellar shell extending all around. Therefore, many detector pixels (especially those close to the central star within the extent of the shell) simply scan over the shell most of the time, and no sky information is recovered. While modified ADI algorithms have been proposed for extended disk sources [10], limitations of the algorithms have recently been investigated quantitatively [11].

Because of the nature of the extended shells of our target sources (i.e., the circumstellar dust distribution in 4π steradians by default), our data are not exactly suited for these algorithms to work properly to suppress the PSF of the central star: it turned out that both the central star AND the circumstellar shell were suppressed by self-subtraction. Instead, we resorted to employ a more basic PSF subtraction technique using a still cleaner PSF constructed with ADI methods for one of the targets without an obviously extended shell.

4. Results

Figure 1 shows PSF-subtracted images of the target PPN candidates associated with an extended nebulosity, constructed from data taken with the ADI method. The PSF reference image was recovered from data taken with the ADI method for one of the targets that showed the least

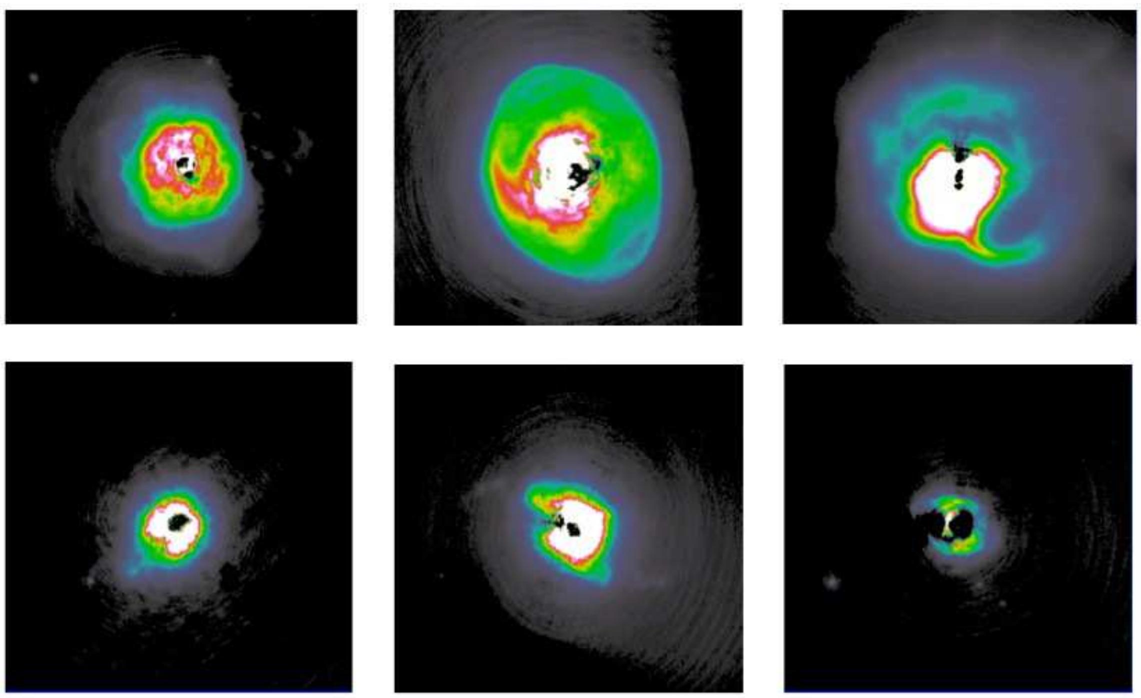

Figure 1: PSF subtracted PPN images using an ADI-processed reference PSF image. From top left to bottom right, HD 179821, IRAS 07134+1005, IRAS 11385-5517, IRAS 08005-2356, IRAS 12175-5338, and IRAS 08143-4406. The field of view size is $7.7'' \times 7.4''$ except for that of HD 179821, which is $10'' \times 9.6''$.

amount of extension (IRAS 08544-4431). The PSF reference image was a straight median of a series of exposures obtained while the image rotator turned off. This PSF reference was then scaled and subtracted off from each exposures of the target sources, before each frame was de-rotated by the amount of the parallactic angle of the time of observations and averaged.

HD 179821 image shows much greater detail of the material closest in to the central star, with respect to previous studies that revealed concentric arcs. In IRAS 07134+1005, the inner shell structure is more clearly revealed compared with the previous direct imaging which captured the general oval shape of the shell. While the general pinwheel structure is shown in previous images of IRAS 11385-5517, our new image shows the north to north-western structures and the southern pinwheel arm more clearly. IRAS 08005-2356 was previously known to have a bipolar structure elongated in the SE-NW direction. The SE lobe is shown more clearly in our new image. The bipolar nature of IRAS 12175-5338 was already known, but our new image shows much greater detail on the pinwheel arms of the circumstellar material. The elliptical structure of IRAS 08143-4406 with lobes pointing to the east and west is verified, and the presence of possible companions are recognized.

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