Coronography at La Silla: High Resolution Imaging of Faint Features Near Bright Objects

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Introduction

Some of the more interesting astronomical sources happen to lie very close to bright objects. If the source is very faint, it becomes extremely difficult to discern it against the glare of the bright object. This situation arises, for example, when attempting to image the ionized tori around satellites such as Io, protoplanetary or circumstellar systems of nearby stars, accretion disks within close binaries, faint emission nebulosities in the vicinity of old novae and possible fuzz around bright quasars. In all these cases, it is imperative to reduce dramatically the scattered light in the wings of the bright object seeing disk and/or to prevent the bright object from saturating the detector and thereby disabling it in the adjacent areas. The latter effect can be important even for relatively faint objects such as 15th magnitude quasars if long integration times are required.

Accomplishing this objective would open up a very fertile field of inquiry; one that is ideally suited to the performance characteristics of modern high resolution, large aperture telescopes and detectors. Success requires a well-designed coronograph coupled to a high quality photon collecting device located on a site with excellent seeing conditions. This note briefly describes the techniques we have devised in our first attempts with a simple coronograph mated to the 2.2-metre MPI Cassegrain telescope at La Silla and some of the results obtained in the first year of operation. A more complete description of the experimental and data analysis techniques and the scientific results can be found in the references at the end of this article and available from the authors.

Experimental Setup

The optical configuration of our observational setup at La Silla is shown schematically in Figure 1. Light from the object under investigation is gathered and focused by the f/8 MPI 2.2-metre Cassegrain telescope onto a blackened photoetched mask located in the focal plane. This occulting mask is shaped in the form of a long thin wedge which can be moved longitudinally by a micrometer in order to vary its projected width in the sky from 2 to 10 arcseconds depending on seeing conditions, source brightness, etc. It can also be moved transversely to occult any desired portion of the field of view. Following the mask, an achromatic doublet reimages the telescope focal plane with a magnification of 5 onto the detector so that the effective focal ratio of the system becomes f/40.

An apodizing mask especially designed to reduce diffracted stellar light from the 2.2-metre telescope pupil is located in the exit pupil and is rigidly attached to the lens mount to ensure that it remains there as the coronograph is focused. The mask obscures 30 per cent of the exit pupil close to the images of the entrance pupil edges. After this mask, the light passes through optical filters in a rotating commandable two-wheel assembly mounted just in front of the detector. In our two runs of September and November 1986 at La Silla, we employed the 512 × 320 30 micron square pixels RCA CCD. In this particular configuration, each pixel corresponds to $5 \cdot 10^{-3}$ square arcseconds in the sky with a total rectangular field of view of 22.5 by 35.9 arcseconds.

The optical and detector system just described was calibrated absolutely using bright, stable stars as calibration sources. Using standard Johnson B, V, and R and Cousins I filters available at La Silla (ESO filter numbers 445, 446, 447 and 465), we obtained overall peak counting efficiencies between 4,000 and 8,000 Å of 0.2 to 0.4 CCD counts per photon depending on bandpass. The transmission of the achromatic doublet decreases rapidly below 4000 Å and is essentially opaque below 3500 Å. Thus for U band measurements the lens should be replaced by a singlet of fused quartz or silica and the detector changed to the UV sensitive GEC CCD available at the 2.2 metre.

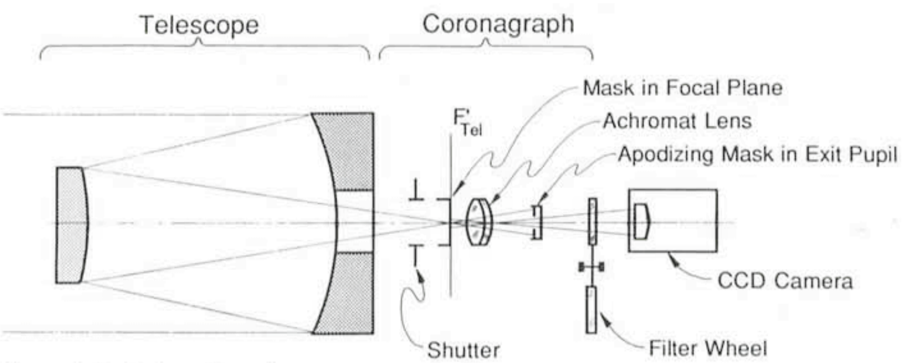

Figure 1: *Optical configuration.*

Observing Methodology

First, the coronograph is focused by adjusting the position of the lens mount until the image of the occulting wedge under flat field illumination comes into sharp focus. The coronograph comes equipped with internal LEDs to provide such illumination so that the focusing can be carried out even when the telescope is not in operation. Second, a suitable star is made to fall somewhere on the unocculted area of the detector through a broad band filter and the resultant image is used to focus the telescope secondary. The coronograph need not be refocused if a filter is changed since the filters are in an f/40 beam. Third, a suitably opaque neutral density filter (ND3 or 4) is moved into the beam and the bright primary source acquired.

Using the telescope TV autoguiding system described by Duchateau and Ziebell in the *Messenger* No. 45, 1986, the source is placed behind the occulting wedge in a series of short acquisition exposures. With a series of increasingly smaller offsets, the source is precisely centred behind the occulting wedge. This is accomplished by making the spillover light distribution above and below the wedge obtained with progressively less ND attenuation as symmetrical as possible. Finally, any ND filter remaining is removed and the long exposure in the specified bandpass be-

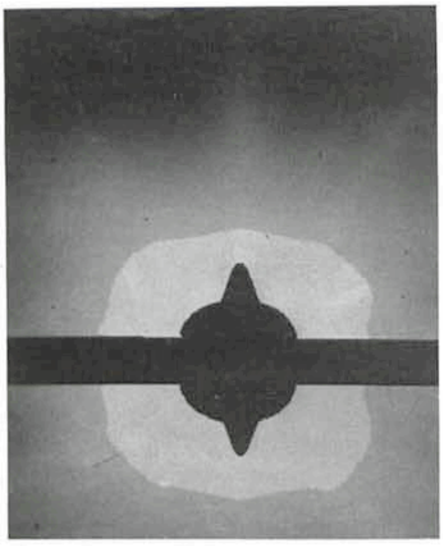

Figure 2: *Image of Alpha Pictoris. The image has been flat fielded, and minor blemishes have been removed. The horizontal bar is the occulting mask and has been masked black. The masked circular area in the centre with triangular appendages is due to saturated and bleeding pixels. The deviations from circular symmetry are due to instrumental scattering and diffraction effects. The image is truncated at 5,000 counts, and has been displayed with the image greyscale changed to give equal numbers of pixels at any given intensity. (Histogram equalization.)*

gun. If a faint feature is expected to be lost in the light from the wings of the bright object seeing profile, the telescope is moved to a control star nearby and the procedure just described repeated. After some practice, the overhead time used to acquire and precisely register the source can be kept within approximately 20 minutes. This time is set mainly by the time necessary to read out, process, and display the relevant CCD acquisition images. A detector with real time display capabilities or a faster data handling system for the CCD would obviously shorten considerably this set up period and allow a faster turn around. This is a critical factor for a lengthy survey programme.

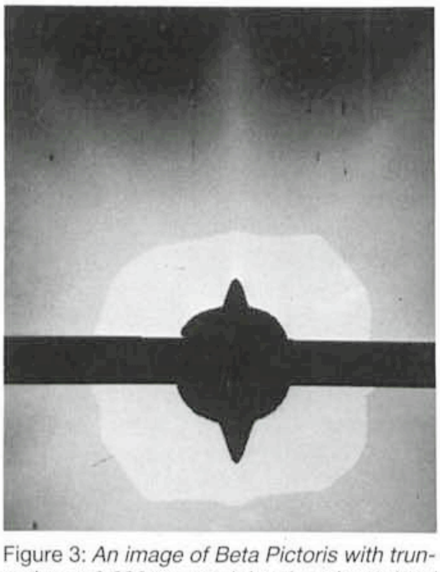

Figure 3: *An image of Beta Pictoris with truncation at 3,000 counts. It is otherwise treated identically to that of Figure 1. All instrumental effects are similar but there is an additional bulge in the image at bottom left (NE) through top right, due to the circumstellar disk.*

Data Analysis and Results

All the raw images are processed in a standard way to prepare them for scientific analysis. The CCD bias level and the variations in response across the detector area are removed by subtracting a constant bias level and dividing by an appropriate flat field. Overclocked, saturated pixels, and bad columns are easily located and masked out so that they will not contribute to the rest of the processing. Cosmic ray events and local CCD defects are also located by comparison with neighbouring pixels using standard statistical tests and iterating to avoid including bad pixels in the averaging process. Finally, the edges of the occulting mask are defined interactively and stored in a file associated with the image. No further user interaction is required in the subsequent processing which can proceed automatically.

The results of this process are shown in Figures 2 and 3 that represent images of Beta and Alpha Pictoris, respectively, taken with the system we have just described with the R band filter on the night of November 27, 1986. Beta Pictoris is a star suspected of having a giant protoplanetary system seen edge-on in emission surrounding the central star while Alpha Pictoris is used as the reference star. Both images are mainly

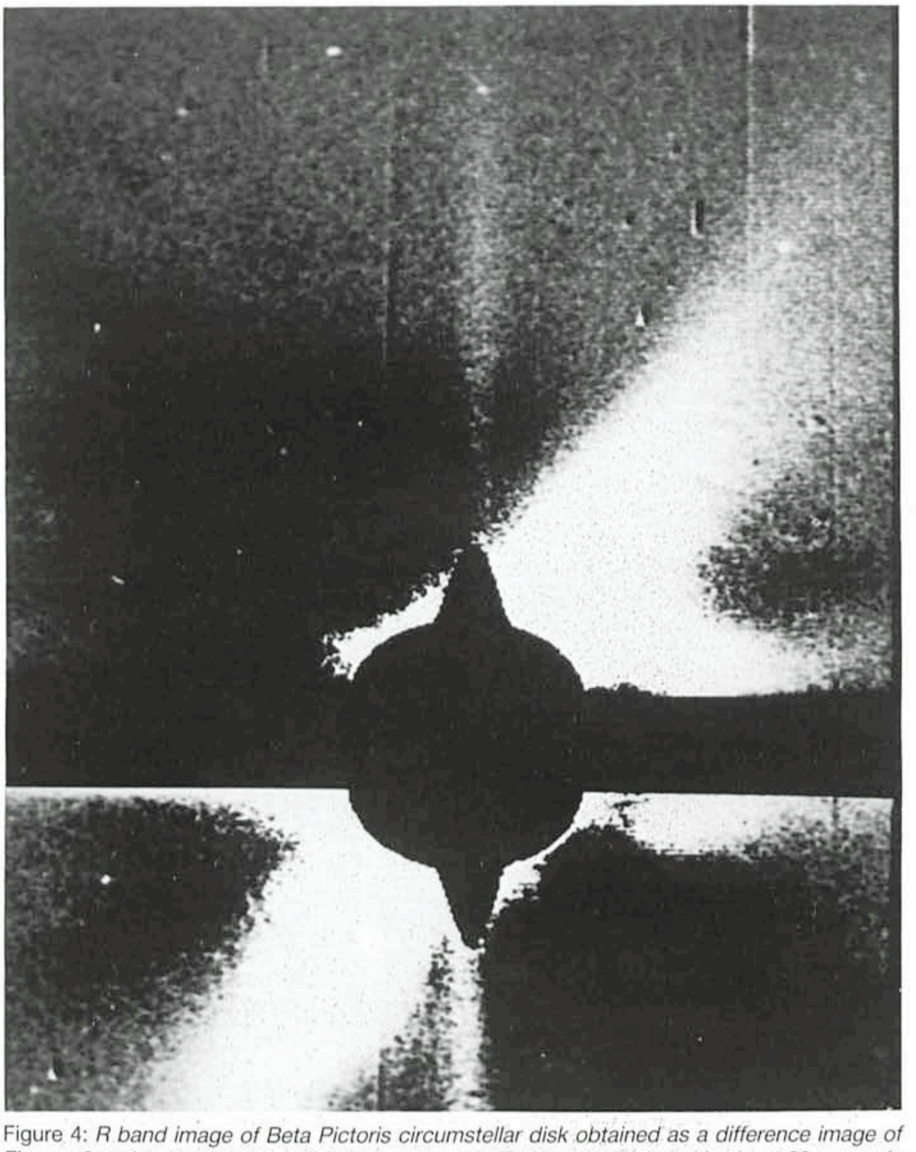

Figure 4: *R band image of Beta Pictoris circumstellar disk obtained as a difference image of Figures 2 and 1. North is up and East is to the left. The image displayed is about 23 arcsec in width. The disk extends diagonally from NE to SW. The dark portions of the image are due to saturated pixels or the focal plane mask. The bright line running vertically through the frame centre, and light close to the mask particularly to the right of centre are due to residual diffractive scattering.*

composed of the stellar seeing disk with small contributions due to scattering within the instrument and, of course, for Beta Pictoris, the circumstellar disk. This feature, however, is almost lost in the image shown in Figure 2 without benefit of a direct comparison with the reference image shown in Figure 3.

Although a feature running in a roughly NE to SW direction through the Beta Pic image, without a corresponding one to be discerned in the control image, stands out rather clearly in the image shown in Figure 2, considerably more analysis effort has to be expended in order to generate a photometrically true or correct image of the immediate surroundings of Beta Pictoris. Details of the complex data processing techniques used to subtract the reference image of Alpha Pic shown in Figure 3 from that of Beta Pic in Figure 2 are given in Reference 1. The basic problem to be solved is to make the result of the analysis as free as possible from assumptions, biases and subjective judgements as possible. In other words, it was taken as axiomatic that no user interaction would be permissible and no assumptions about the characteristics or even the existence of circumstellar features would be allowed. This is a crucial but often neglected attribute of any method applicable to the interpretation of astronomical data of this type. The best algorithm chosen essentially consisted of a truncated least squares fit between the two images allowing the relative intensity, overall background and spatial registration to vary. The best values for these parameters obtained this way were then used by the programme to subtract the reference from the Beta Pictoris image.

The result of this procedure for the Beta Pictoris case is shown in Figure 3. This figure dramatically illustrates the power of the technique briefly described here. The image is photometrically accurate in that counts at any point in this image are linearly related to the true emitted intensities of the protoplanetary disk through the absolute calibration of the optical and detector system used. A standard ratio image, for example, would not satisfy these basic requirements and, thus, cannot represent a true image of the stellar surroundings dependent as it still is on spurious and contaminating effects of the specific detecting system employed in the investigation. This and other images of the Beta Pictoris disk taken at La Silla in the B, V, R and I_c bands represent the first visible images of this fascinating feature.

The physical implications of these measurements on Beta Pictoris and other candidates are described in detail in Reference 2. For Beta Pictoris, the fact that the variations in brightness of the disk in the broad B, V, R and I_c bands quite closely mimic the stellar spectrum, almost certainly implies that the emission we detect is due to scattering of the stellar radiation from particles of average size much larger than one micron diameter. This, in turn, indicates that some sort of accretion process has been active in the protoplanetary nebula to form large grains from the approximately 0.1 micron sized particles commonly found in interstellar space. It should be noted that the IRAS infrared excess emission reported for this star by Gillett, 1986 (Reference 3) that initially triggered interest in this particular system does not necessarily have to originate from the same material responsible for the scattering observed in the optical.

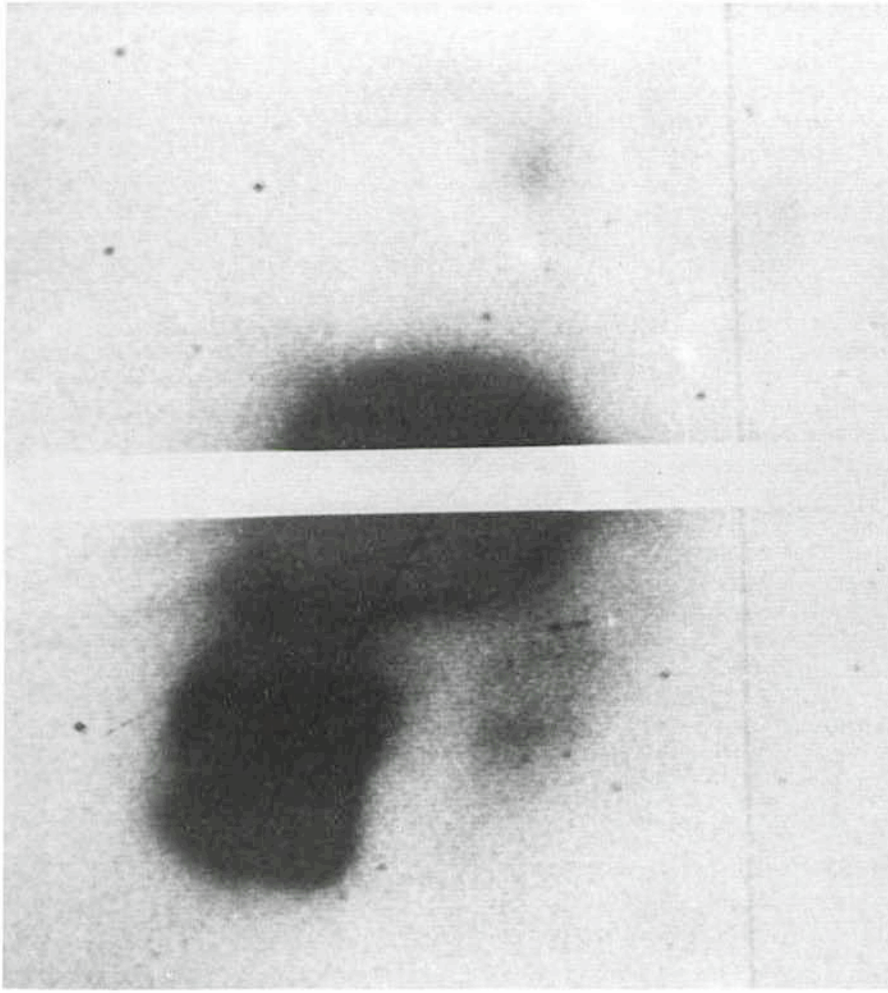

Figure 5: *A narrow band NII image of R Aquarii, a variable binary with known emission of ionized knots along a collimated axis. The knots are resolved clearly in the raw data but are overexposed in this image to reveal the presence of faint loops of material to the North of the star. The directions are the same as in the previous figures.*

A slightly different application of the coronographic technique just described is shown in Figure 4 wherein an area around the symbiotic Mira variable R Aqr is investigated in some detail. This fascinating system is quite likely to consist of a mass losing Mira variable and a hotter blue companion accreting a portion of that mass via an accretion disk (see Solf and Ulrich, 1985, and references therein). Although this system is known to be one of the most complex observed so far, probably, mainly because it is so close (200–300 parsecs by most estimates), some of the most exciting phenomena occur deep within the inner nebulosity extending out to 10–15 arcseconds at most from the central object. The morphology and physical characteristics of this nebulosity are not well known, principally because of the difficulty of imaging accurately and reliably within a few arcseconds of the bright Mira whose visual magnitude varies periodically from m_v = 6 to 11 in 387 days.

An obvious solution to this problem is offered by the coronographic technique whereby the bright Mira is occulted by the 2 arcsecond wide wedge as shown in Figure 4. This allows long integration time exposures through narrow band filters tuned to bright emission lines such as Hα and the forbidden [NII] 6583 Å. Short duration broad band R exposures appropriately subtracted from the narrow band images allow an even better view of the line emission region around this object. The image shown in Figure 4 also illustrates graphically the potential of this technique as both previously known and unknown bright and faint features throughout the inner nebulosity can be readily discerned and accurately measured down to approximately one arcsecond of the Mira without much trouble. Especially obvious is the famous jet made up of several knots extending in a generally northern direction towards the bottom of the figure but faint wisps, knots, and a counter jet extending to the limits of our image in the southwest are also clearly discernible against the sky background. Direct comparisons of images taken in the light of several emission lines of elements in varying ionization stages show remarkable differences revealing a complex temperature and electron density structure within the nebulosity. These data should prove quite useful in establishing and elucidating the mechanism responsible for the observed activity in this enigmatic system.

More observations of a number of interesting objects with this technique at La Silla are being planned for the near future. The authors welcome suggestions from readers of this publication for improvements, additions to and ideas for new applications of the basic technique described here. If you have a favourite object that might benefit from an investigation with our coronograph, please contact us so that we may explore the feasibility of a joint effort.

Acknowledgements

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Search for Supernovae in Distant Clusters of Galaxies

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Supernovae and Cosmology

One of the main problems of cosmology today is to determine whether the universe is open or closed, i.e. if it will continue to expand for ever or if it will recollapse in a far future. The classical attempt to settle the question is to observe some kind of standard candle out to large redshifts, z, and measure the positions of the objects in the Hubble diagram (log (z) versus apparent magnitude). The brightest galaxies in rich clusters have for example been used for this purpose, but significant evolution corrections are expected which are hard to determine with the required precision, and no firm conclusion has been reached as yet.

A more promising candidate for a standard candle is the type I supernova (SN I). SN I events show spectra and light curves which are very alike, and the intrinsic scatter in peak brightness is less than 0.3 magnitude. SNe I occur in spirals as well as in elliptical galaxies. Events in elliptical galaxies are not expected to suffer from any significant interstellar extinction in the parent galaxy, which would otherwise be difficult to correct for with the necessary accuracy. SNe I near maximum rival with galaxies in brightness ($M_v = -19.7$ for $H_o = 50\ km\ s^{-1}\ Mpc^{-1}$). At a redshift of $z = 0.5$ the expected peak magnitude in V is about 22.7 depending on K-correction and the cosmological model assumed. For Friedmann models with $q_o = 0.0$ (open) and $q_o = 0.5$ (transition to closed) the difference is 0.28 magnitude. A modest number of SN I events could therefore provide the evidence for an open or closed universe. Notice, that neither H_o nor the absolute peak magnitude need to be known.

SNe I as standard candles are not supposed to be plagued by uncertain corrections, as are other candidates. The K-corrections can be accurately determined from nearby SNe I, and no change of the supernova characteristics with look-back time is expected.

A well-developed theoretical model for SNe I assumes the deflagration of a white dwarf which is pushed to the Chandrasekhar limit by mass accreted from an evolving companion. In this picture virtually the same event happens every time with no variation of mass and chemical composition. This explains the reproducibility of the phenomenon.

It has recently been realized, however, that a subgroup named SNe Ib exists in spiral galaxies. This subgroup is characterized by the absence of the λ 6150 absorption feature in the spectra. SNe 1b will hardly cause any major problem for cosmological applications as they are about $1^m.5$ fainter than the majority of SNe I. If they are not discriminated by other means they may be discarded because of gross deviations from the predicted apparent magnitude.

The Search Programme

With the launch of the Hubble Space Telescope (HST) it will become possible to do photometry on distant SNe to magnitudes fainter than 25, and the cosmological goal is then within reach. The first and difficult problem is to find the SNe I. G.A. Tammann (1) estimates that a Coma-like cluster at z = 0.5 will show a rate of 0.5 SN I per year within the field of the Wide Field Camera of the HST. However, observing time on the HST is very expensive, and fortunately the job can be performed from the ground. The Danish 1.5-m telescope at La Silla is ideal for the task. The observing time is