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Hα and Hβ Imaging of the Planetary Nebula NGC 6302

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Abstract: NGC 6302 is one of the highest excitation planetary nebulae known. It has an obscured central star with a temperature estimated at 430,000 K. We present here CCD images in Hα and Hβ of NGC 6302, and interpret the differences between the images as being due to extinction caused by dust within the nebula. The dust appears to be concentrated in the core, as expected from infrared observations. There is no evidence of patchy foreground extinction, although there is a slight difference in the average extinction between the eastern and western lobes of the nebula. A comparison between the Hα image and a 5 GHz map gives a dust extinction of $\Delta AV \sim 3.5$ to the central star. The outer contours of the 5 GHz map are not in good agreement with the optical images, and further observations at this frequency would be useful.

1. Introduction

NGC 6302 is the brightest and most dramatic example of a bipolar planetary nebula. With galactic coordinates of $l = 349°$ and $b = +1°$, the nebula lies in a region of heavy and patchy obscuration. The first detailed study of the nebula was made by Minkowski and Johnson (1967) who used some superb Hα + N II plates and coudé spectrograms (taken by O. C. Wilson with the 200 inch telescope) to comment on the object's visual appearance and velocity structure. They deduced the patchiness of the interstellar extinction in areas of sky neighbouring NGC 6302 on the basis of the apparent distribution of faint field stars, and wondered if the obscuring clouds could be modifying the appearance of the nebula.

NGC 6302 is a strong thermal source of radio continuum, becoming optically thin above ~3 GHz at a flux density of ~3 Jy. Almost all the emission comes from the central 15″ (Terzian, Balick, and Bignell 1974), in a region where the optical flux appears to be obscured by a central dark lane. For comparison, the optical extent of the nebula is 3′ − 4′. Detailed radio VLA maps of the core in the continuum and in the H76α line were published by Rodríguez *et al.* (1985). They showed that most of the continuum radiation comes from an elliptical patch with outer diameter ~10″. Assuming that the ellipse results from the projection of a toroidal structure they estimated that NGC 6302 is inclined at an angle of 45° to our line of sight.

The central star is most likely embedded within the radio core — so far it has resisted detection. Ashley and Hyland (1988) observed strong lines from [Si VI] at 1.96 μm, and [Si VII] at 2.48 μm, and used the line ratios to estimate the star temperature as $4.3 \pm 0.5 \times 10^5$K, making it the hottest such object known.

This paper describes the results of an observational programme to image NGC 6302 in the light of Hα and Hβ. By ratioing the images it is possible to examine the variations in reddening across the nebula.

2. The observations

The observations were obtained in 1988 July at the f/8 focus of the 40 inch telescope at Siding Spring Observatory. The detector was an unintensified CCD camera system manufactured by Astromed. The camera uses a GEC P8603 CCD chip, dye-coated to improve the blue sensitivity, and cooled with liquid nitrogen to reduce the thermal noise to $\sim 9e^-$. The CCD images consist of 587 by 375 pixels, with a plate scale of 0″.56 per pixel.

Narrow-band interference filters were used to define the

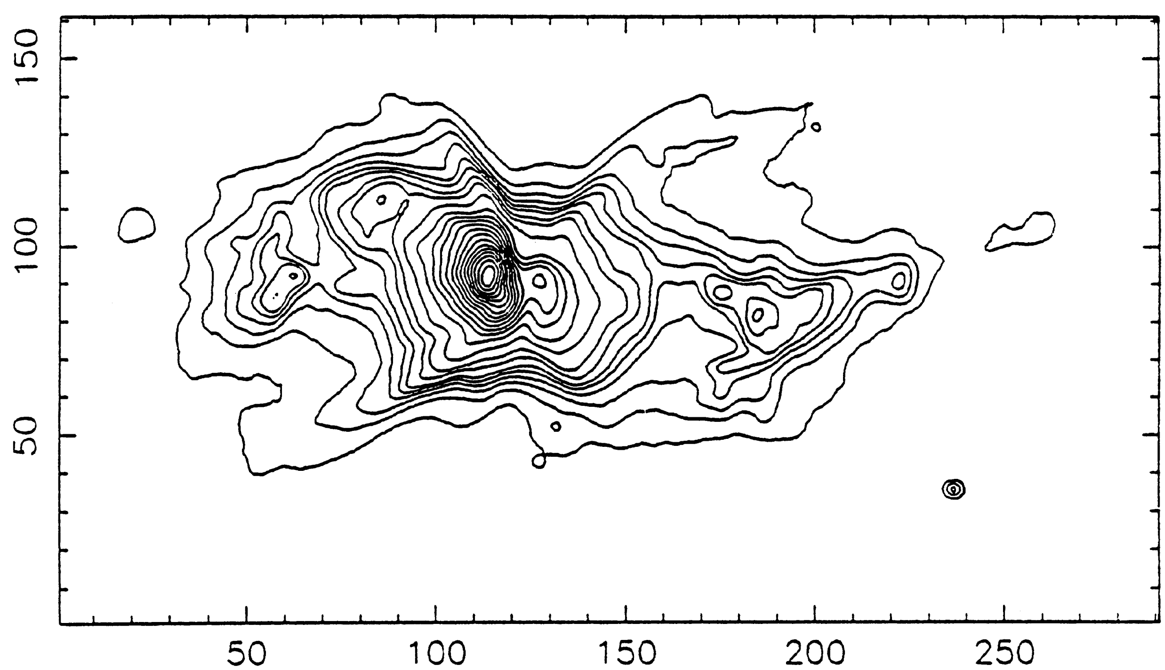

Figure 1 — NGC 6302 imaged in Hα. The sum of eleven images obtained with the CCD camera of the 40 inch telescope at Siding Spring Observatory. The contour intervals are approximately logarithmic, and are at 0.90, 0.78, 0.67, 0.58, 0.50, 0.43, 0.36, 0.30, 0.25, 0.20, 0.16, 0.13, 0.10, 0.07, 0.05, 0.04, 0.03, 0.025, 0.02, 0.015, 0.01, and 0.005 of the peak flux. North is up, east is to the left, and the scale is in units of 0″.5.

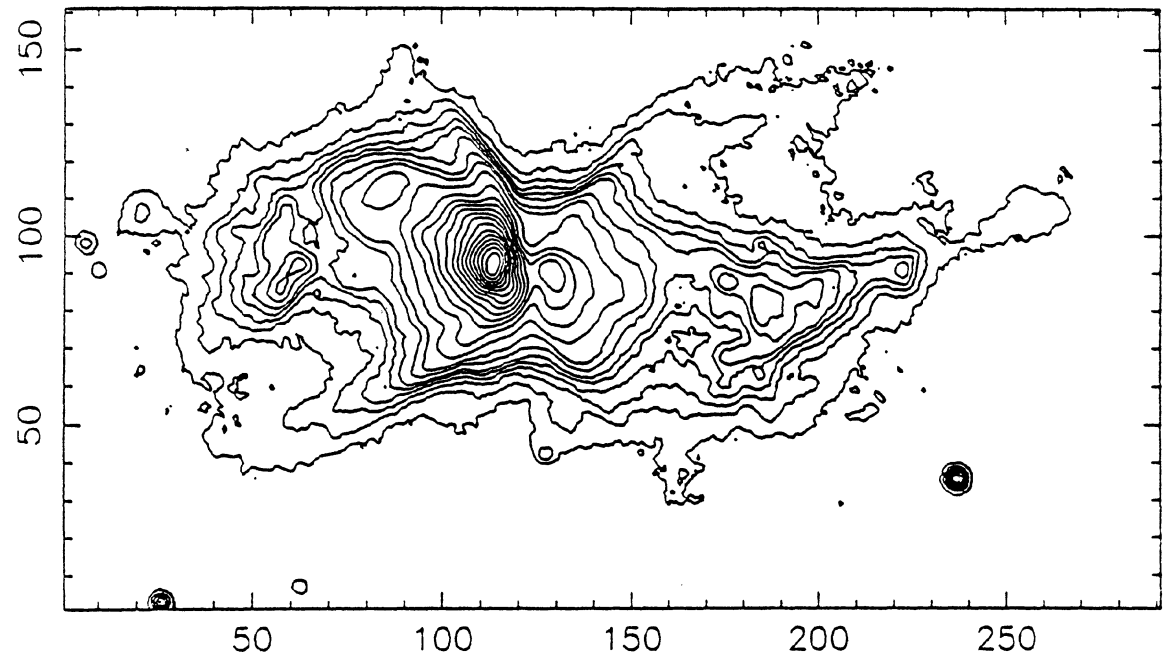

Figure 2—NGC 6302 imaged in Hβ. The sum of ten images. The contour intervals, scale, and orientation are the same as for Figure 1.

wavelength regions of interest. The Hα filter was centred on 6563 Å, with a full-width at half-maximum (FWHM) of 15 Å; the Hβ filter was centred at 4861 Å with a FWHM of 17 Å. To quantify the effect of contamination from other lines and the continuum, the filter profiles were convolved with a spectrum of the bright eastern lobe of NGC 6302 obtained using the cassegrain spectrograph of the 74 inch telescope at Mt Stromlo Observatory. The Hα filter contamination was $<0.5\%$; for Hβ the contamination was $<3\%$.

Over thirty 1000-second exposures of the nebula were taken at each wavelength. To assist in smoothing out possible non-uniformities in the flat-fields, the position of the nebula on the CCD was shifted between each exposure. After the usual bias subtraction, linearity correction (necessary for the pre-1989 CCD camera), flat-fielding, and cosmic ray removal, the best images (11 for Hα and 10 for Hβ) were shifted, rotated, and resampled to bring them to a common coordinate system aligned north-south with 0″5 per pixel. Each image was then repeatedly smoothed using a two-dimensional 3×3 point Hanning filter till its point-spread function matched that of the worst case image (1″9 FWHM, 3″7 full-width at one-eighth of maximum). Smoothing is essential before attempting to compare images by dividing them, since otherwise spurious structures will be introduced, particularly in regions where the spatial derivative of the intensity is high. Finally, the images were coadded and contoured to produce Figures 1 and 2.

3. Interpretation

A preliminary inspection shows little difference between Figures 1 and 2. The differences are exaggerated in Figure 3 which shows the result of dividing Hβ by Hα (this order was chosen since the Hα image has a better signal-to-noise ratio and more flux in the outer parts of the nebula), with a mask applied to exclude areas where the ratio becomes dominated by noise. The contour plot appears confused in the east and west lobes since the ratio of Hβ to Hα is almost constant, fluctuating between two contour levels.

Note that since the Hβ and Hα images were not individually flux-calibrated, the ratio image is also uncertain by a multiplicative constant. It would be possible to calibrate the ratio image using the results of long-slit spectroscopy, but, due to the uncertainty in published slit positions, and the considerable spatial variations in the ratio, this was not done. Instead the ratio in the outer reaches of the nebula was set equal to the intrinsic Case B recombination value appropriate to an H II region with an electron temperature of between 10,000 K and 20,000 K, i.e., 1/2.8.

Figure 3 shows no evidence for the large extinction variations in the outer lobes of the nebula that have been postulated by Minkowski and Johnson (1967), Phillips, Reay, and White (1983), and Rodríguez *et al.* (1985). There is, however, a pronounced decrease in the Hβ/Hα ratio towards the core. One explanation for this is absorption due to dust within the nebula, and indeed Lester and Dinerstein (1984) have observed infrared continuum emission from large amounts of dust present within the central area of the nebula. Another possibility is that the intrinsic Hβ/Hα ratio is different in the core. A mechanism that would decrease the intrinsic ratio is collisional excitation of neutral hydrogen by hot electrons. However, the fractional abundance of neutral hydrogen close to the central star is very low, and T_e has been measured at less than 20,000 K (see, for example, Aller *et al.* 1981), at which temperatures the collisional contribution is minor (Osterbrock 1974). In what follows we will assume that the intrinsic Hβ/Hα ratio is simply the Case B value, and that any variations are caused by extinction.

Figure 3 shows that the outer-west region of the nebula has slightly more extinction on average than the outer-east regions, which could be due to material local to the nebula. The sense of the difference implies that the west arm is further away, in agreement with radial velocity data (see, for example, Minkowski and Johnson 1967). To quantify this effect we used the ratio image to measure the average value of Hβ/Hα in a reference area of 370 square arcseconds in the outer-east region, and equated this with a logarithmic extinction at Hβ of

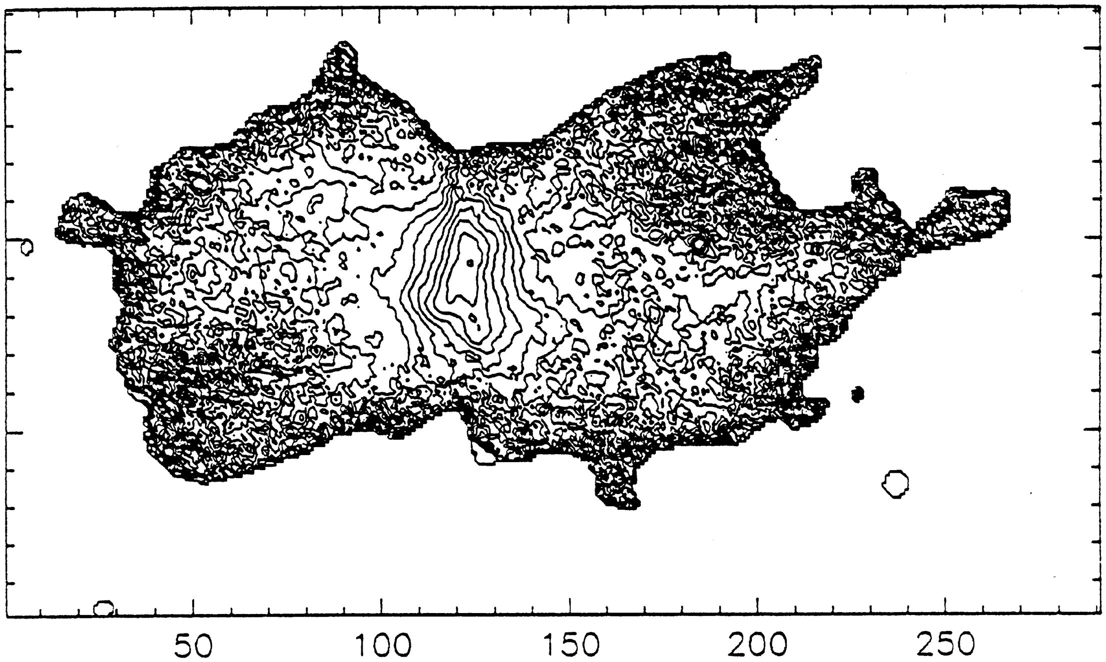

Figure 3—NGC 6302 imaged in the ratio of Hβ to Hα. The contours are in equally spaced intervals ranging upwards from 0.14 in the centre in increments of 0.0147.

$c=1.220\pm0.010$ (after Aller *et al.* 1981; the error reflects the standard deviation of the pixel values). We then selected an area of 230 square arcseconds in the outer-west region, and obtained $c=1.237\pm0.006$. The lowest extinction region we could find was a 95 square arcsecond area in the north-east which gave $c=1.191\pm0.010$. So there are slight, but significant, variations in the extinction in the outer regions of the nebula. It is clear, however, that the visual appearance of the nebula is not greatly affected by patchy foreground extinction.

Figure 4 is a detailed view of the core region in Hβ, Figure 5 shows the same region in the ratio Hβ/Hα and Figure 6 shows 5 GHz contours derived from the Very Large Array data of Rodríguez *et al.* (1985). The 5 GHz image has a spatial resolution of 1″.5 E-W and 2″.3 N-S, closely matching the optical images. Each figure has been superimposed on a contour map taken in Hα. It is clear from Figure 5 that the material causing the extinction covers a large region, at least 25″ × 25″, and is not just confined to the dark lane. The 5 GHz map shows the true distribution of ionized material since it is known that NGC 6302

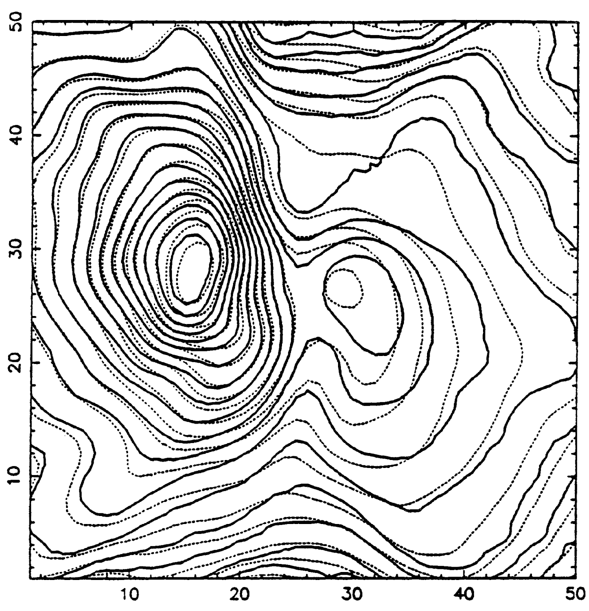

Figure 4—A contour plot of the core of NGC 6302 in Hβ (continuous lines) and Hα (dashed lines). The contour intervals are the same as those used in Figures 1 and 2.

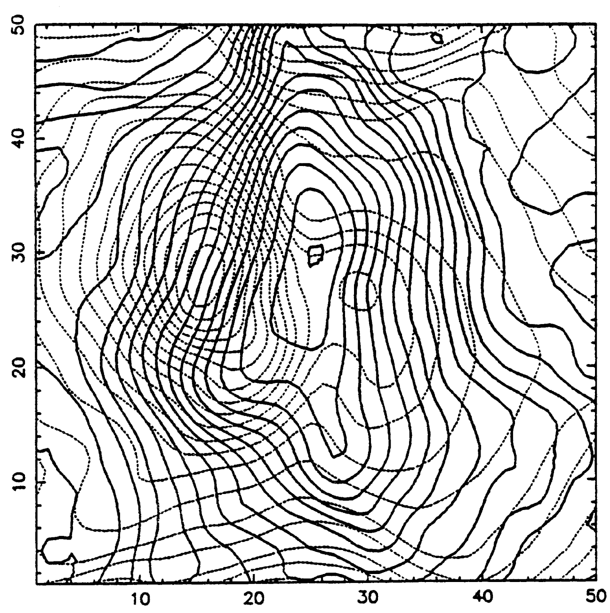

Figure 5—A detailed view of the core of NGC 6302 imaged in the ratio Hβ to Hα. The continuous contours are lines of constant Hβ:Hα ratio, ranging from 0.14 for the central contour, upwards in increments of 0.012 (i.e., 0.140, 0.152, 0.164, . . .). The dashed contours are from the Hα image of Figure 1.

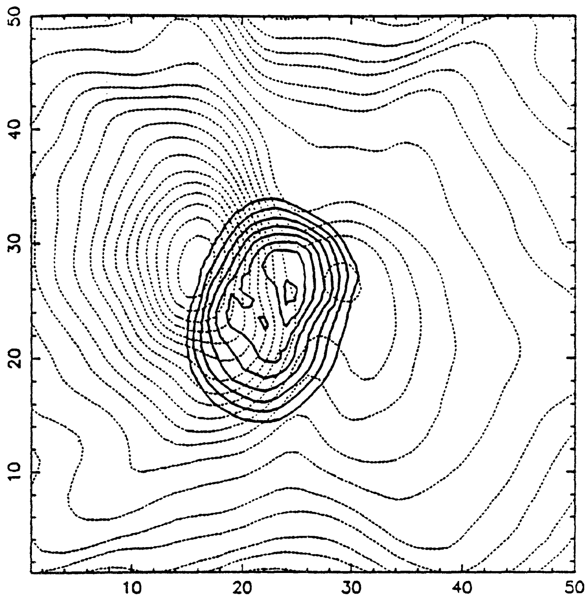

Figure 6—A 5 GHz contour plot of the core of NGC 6302, derived from the VLA data of Rodríguez *et al.* (1985). The dashed contours are from the Hα image of Figure 1. The 5 GHz contours are at intervals of 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, and 0.2 of the peak flux.

becomes optically thin above ~3 GHz (see Rodríguez *et al.* 1985 for a summary of the evidence for this). The dramatic differences between the 5 GHz and optical hydrogen line images must be predominantly caused by intra-nebular dust.

A standard technique used to determine interstellar reddening is to compare the 5 GHz continuum flux from an object with the flux in an optical hydrogen line, usually Hβ. This technique doesn't work for NGC 6302 since the core of the nebula is not optically thin in Hβ. The most one can do is to use the 5 GHz to Hβ ratio to give a lower limit to the excess extinction caused by intra-nebular dust. This task is difficult since the optical and radio images are so dissimilar, even at the lowest radio contours, which implies that the optical radiation comes from different (closer) material, and therefore makes any comparison between the fluxes dubious. It is surprising that there is no correspondence between the lowest radio contours and the optical image since echelle spectra of the bright optical lobes show that they are relatively transparent to Hβ: material is observed both flowing away from and flowing towards the observer. A valuable future observation would be to extend the sensitivity of the radio image to pick up the fainter radiation from the extended lobes.

With these provisos in mind, we find a lower limit to the excess extinction to the central star, additional to the interstellar component, of $\Delta AV \sim 3.5$. This amount of extinction is sufficient to cause the star to appear red despite its intrinsically very blue spectrum. Attempts to detect the star by comparing narrow-band continuum images in the blue and red have been unsuccessful (Ashley 1988).

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