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IDENTIFICATION OF THE CENTRAL STAR OF NGC 7027

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ABSTRACT

The central star of NGC 7027 is unambiguously identified at a position which agrees well with that found by Harlan and Miller, and Atherton *et al.* The visual magnitude of 16.32 ± 0.35 falls in the range of 15 to 20 reported by other investigators and coincides with the estimate calculated by Shaw and Kaler of 16.4 needed to force equality between the hydrogen and helium derived Zanstra temperatures.

For $m_v = 16.3$, $E_{B-V} = 0.85$, $T_* = 180{,}000$ K, and a distance of 900 pc, the central star radius and luminosity are 0.072 $R_\odot$ and 4900 $L_\odot$. The implied central star mass is about 0.65 $M_\odot$ if burning hydrogen and 0.70 $M_\odot$ if burning helium.

Subject headings: nebulae: individual (NGC 7027) — nebulae: planetary

I. INTRODUCTION

The central star of NGC 7027 has been the target of numerous attempts at identification. Due to the high density of the surrounding nebula, the nebular continuum is sufficiently bright (integrated $m_v = 11$ [Kaler 1988]) that finding a faint central star becomes a problem of considerable difficulty. Even observations using narrow-band photography and CCD imaging in line-free regions are dominated by nebular continuum emission.

Liller (1955) derived a lower limit to the magnitude of $m_{pv} > 11.3$ from photoelectric photometry, and relates that Baade was unable to find a central star brighter than 18th mag. Harlan and Miller (1978) used an image-tube camera on a large scale refractor with an intermediate bandpass line-free filter. They identified a stellar image but where not able to derive an accurate magnitude, but estimated that $m_v = 15 \pm 1$. Atherton *et al.* (1979) used an electronographic camera and filters having very narrow bandpasses to identify an enhancement which they associated with the central star. They derived a magnitude estimate of $m_v = 19.4 \pm 1$. Using the IPCS digital detector, Walton *et al.* (1988) estimated the unreddened central star magnitude at 17.7 ± 0.5 which corresponds to an observed $m_v = 20.6$ for $c = 1.37$ (Shaw and Kaler 1982) or $E_{B-V} = 0.85$ (Kaler and Lutz 1985).

Theoretical estimates of the central star magnitude can be derived from nebular properties if a central star temperature can be approximated, effectively applying the Zanstra method in reverse. Shaw and Kaler (1982) derived a magnitude estimate of 16.4 by forcing equality between the hydrogen and helium Zanstra temperatures. Berman (1937) calculated 15.6 using a similar technique, but computed the central star temperature based on the intensity ratio of Hβ to the "nebulium" lines, a ratio which Kaler (1978) has shown to correlate well with central star temperature.

The difficulty in deriving a visual magnitude is underscored by the large estimated errors reported by these observers. The principle challenge for stars embedded in nebulosity is the determination of the underlying background to be removed from the simulated aperture photometry when using two-dimensional detectors. In these situations the background can (and does) vary significantly at the arcsecond scale, and so an accurate measurement requires (1) flattening of the underlying background to remove high frequency spatial variations, and (2) a small radius for the simulated aperture to minimize the effects of residual background uncertainties. A technique to achieve a good measurement is described below.

Having derived an accurate visual magnitude for the central star of NGC 7027, it is then possible to compute the Zanstra temperature by comparison of m_v to the nebular Hβ and/or He II λ4686 fluxes. The ratio of the stellar radius to the distance can then be calculated. If an independent estimate of the distance is available, the radius and total luminosity of the central star may also be determined. When combined with the temperature, the central star can be located on a theoretical H-R diagram to estimate its mass and evolutionary age.

II. OBSERVATIONS AND REDUCTIONS

In cases for which the background is the dominant noise source in a measurement, it is essential to obtain very high signal-to-noise (SNR) observations. This is generally not possible with photographic techniques or high-speed digital detectors. The CCD detector, however, is capable of yielding very high SNR observations which may be co-added to further enhance the accuracy of the observations. If it is possible to obtain an image consisting only of the background, then the visibility of the primary target can be greatly improved by digitally subtracting the background image from an image which includes the target.

This can be achieved for the central star of NGC 7027 in the following way. The background noise is represented by the nebular continuum plus any weak emission lines which are included in the bandpass of the imaging filter. The filter should be chosen to avoid as many strong lines as possible. Several exposures are taken through this filter to achieve a high SNR. A second series of exposures are also taken through a narrow filter which passes a strong emission line such as Hβ. Because both the intensity of Hβ and the intensity of the nebular continuum (primarily derived from hydrogen free-free and free-bound emission) are proportional to the square of the nebular density, variations in the nebular background will be tracked by similar variations in Hβ.

Tracking failures will exist if the temperature or ionization

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structure of the nebula is not uniform, or if emission from other sources is included in either or both of the two filter bandposses. For example, the contribution to the NGC 7027 nebular continuum from singly and doubly ionized helium is 27% near 5260 Å. Should a region exist in which the helium were fully doubly ionized, then the total continuum would increase by nearly 30%, an increase which would not have a counterpart in the Hβ flux. It is possible that a subarcsecond region such as this may be confused with the identification of a stellar object, such as the central star.

The background (Hβ in this case) image is aligned with the primary (continuum) image to account for any telescope shift or change in scale between the two series of exposures, and scaled to force the brightness levels in the nebular images to be equal. A subsequent subtraction is expected to produce an image of the central star embedded in a region of increased noise where the incoherent photon noise of the two images adds. In practice, the noise region contains residuals of the subtraction process in which the two images do not perfectly cancel. Potential causes for subtraction residuals are (1) tracking failures as mentioned above, (2) spatially variable reddening across the object, (3) seeing variations between the two image sequences, (4) numerical errors in shifting (especially for spatially undersampled data) in which the two-dimensional interpolation is a smoothing process, and (5) detector limitations such as imperfect charge transfer with CCDs.

Continuum and Hβ images were obtained at the Kitt Peak No. 1 0.9 m telescope on 1987 November 23 using a Tektronix 512 × 512 CCD. The filters had central wavelengths and bandpasses (FWHM) of 5290 Å, 4857 Å and 273 Å, 28 Å respectively. The continuum filter also passed about a dozen very weak emission lines plus a modest contribution from He II λ5411 having an intensity relative to Hβ of 7% (Kaler *et al.* 1976). The Hβ filter passed the weak line from He II λ4859 which has an intensity relative to Hβ of about 2% (Kaler *et al.* 1976). From Pottasch (1983), for example, the flux in the continuum bandpass is expected to be about 60% of the Hβ flux, and so flux from the He II λ5411 line contributes an additional 10% to this bandpass.

Both images consist of sums of four successive CCD frames. Exposure times were 5 minutes and 2 minutes for the continuum and Hβ frames, respectively. These exposure times were short enough to produce images lying well within the linear operating regime of the CCD and yielding a SNR in each pixel near the center of the nebula of at least 300.

After summation of the individual frames, the Hβ sum was shifted to the coordinate system of the continuum image. The relative shift was determined from the centroids of four bright stars in each image. The uncertainty in the shift was less than 0.1 pixel (0".0774) in both R.A. and decl. The magnitude of the shift was less than 0.5 pixels in each direction. The Hβ image was then scaled and subtracted from the continuum image interactively until the nebular contribution was best balanced. The unsubtracted continuum image is shown in Figure 1 (Plate 8) (at two contrast levels), and the subtracted image is shown in Figure 2 at high contrast. Figure 3 illustrates that the profile of the candidate central star is identical to the bright star 10".35 to the east.

The central star is clearly visible in the subtracted image, and barely visible in the unsubtracted image. It is evident that

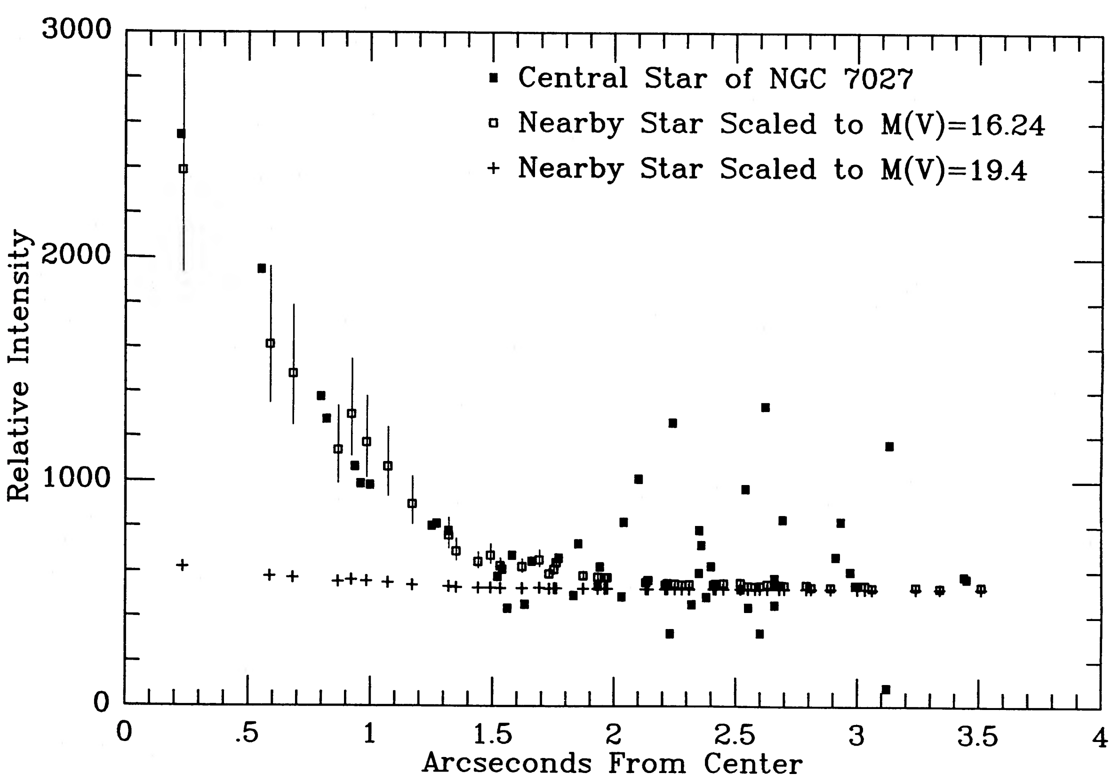

FIG. 3.—A radial profile of the central star (*filled boxes*) of NGC 7027, compared with a profile of the star 10".35 to the east (*open boxes*). The nearby star has been scaled in magnitude (see text) to match the amplitude of the central star candidate. Vertical bars indicate scale errors of ±0.3 mag. The lower trace (pluses) is the profile of the nearby star but scaled so that it would appear as a star of magnitude 19.4. In all cases, the ordinate is instrumental counts where each count represents 3.2 detected photons.

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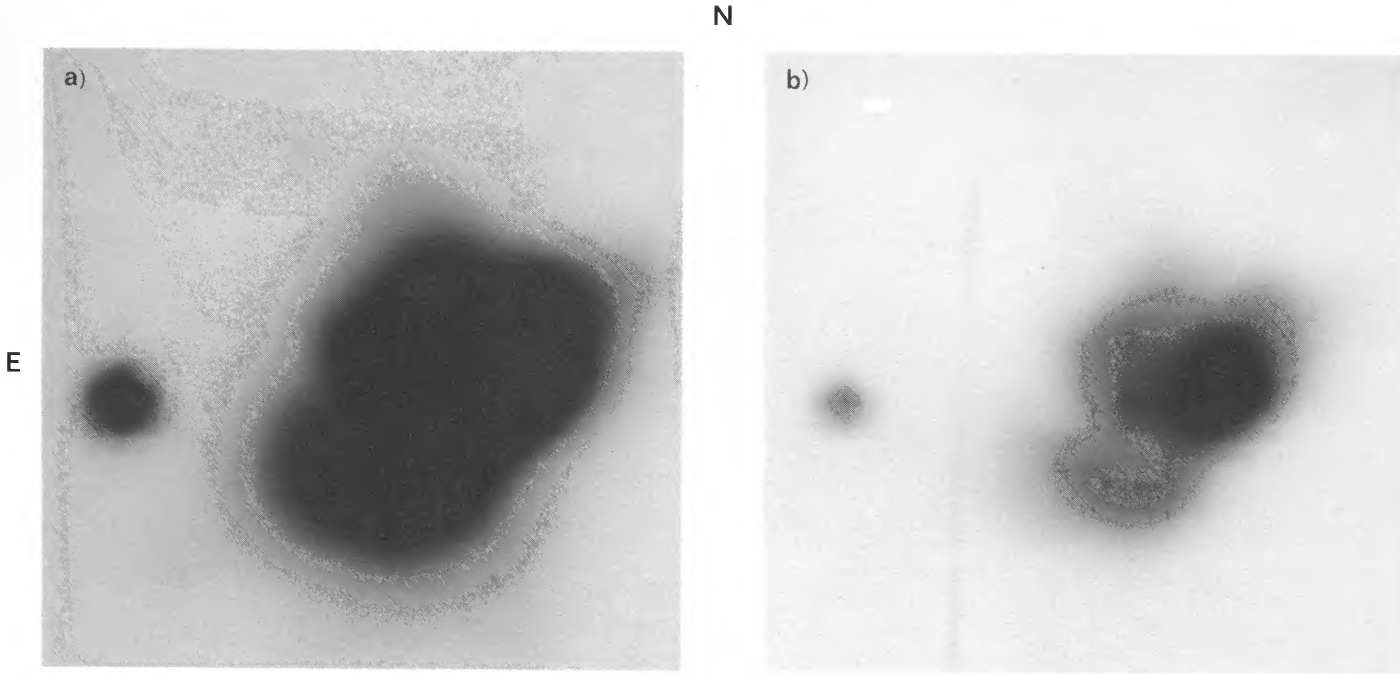

FIG. 1

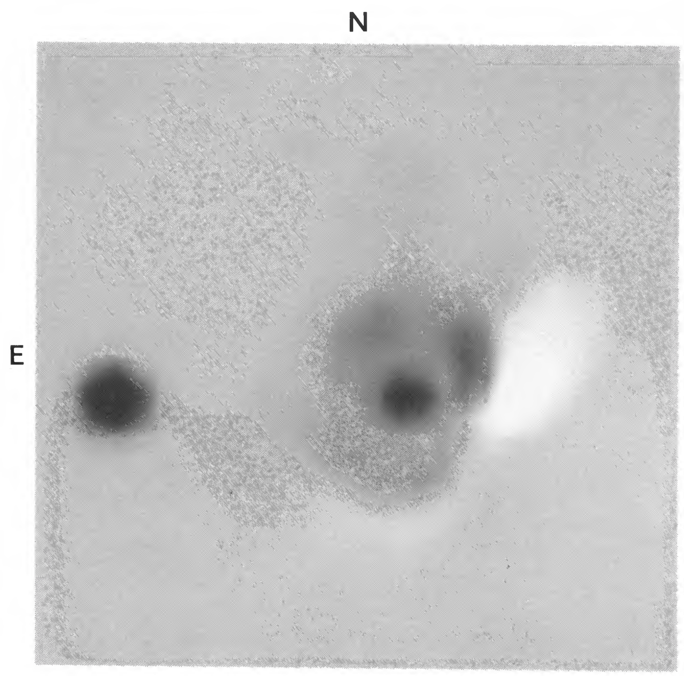

FIG. 2

FIG. 1.—A CCD image of NGC 7027 in the continuum bandpass. Two contrast levels are shown. The image on the left (*a*) is displayed so that outer parts of the nebula are visible, while the right-hand image (*b*) is displayed so that the central star candidate is made visible. Both pictures represent the same data. Each image is 24″ on a side.

FIG. 2.—A CCD image of NGC 7027 after subtracting a shifted and scaled image taken through an Hβ filter. The image is presented at a contrast level comparable to Fig. 1*a* to illustrate the effectiveness of the subtraction technique. Some oversubtraction is present where the bright knot of NGC 7027 is imaged, and undersubtraction in a ring around the central star. The subtraction residuals can be understood as the effect of differental reddening across NGC 7027. The image is 24″ on a side.

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any measurement of the magnitude derived from unsubtracted data, photoelectric, photographic, or CCD based, is subject to a considerably greater uncertainty than after the subtraction.

Low-level ($<10\%$) residuals from the subtraction are evident, however. Figure 4 demonstrates that the central star is clearly visible above them. An apparent ring surrounding the central star may be due to the presence of high-excitation lines such as He II $\lambda5411$ in the bandpass of the continuum filter. Other residuals may arise from nonuniformities in the nebula. Based on the similarity in the nebular appearance at Hβ and $\lambda5007$, Hicks, Phillips, and Reay (1976) argue that there is little variation in the nebula in terms of temperature structure. Atherton *et al.* (1979) have mapped the extinction across the face of NGC 7027. It is evident for their Figure 9 that variations up to 1 mag in extinction at Hβ exist relative to the position of the central star. At positions of high extinction excursions, the Hβ subtraction will leave a positive residual relative to the redder continuum image, and the opposite is true as well.

In Figure 2, the positive ring residual corresponds well with positions of enhanced extinction, while the area with a large negative residual (about 4″ east of the central star) is within 2″ of an extinction hole in the map given by Atherton *et al.* The magnitude of the residuals (5% –10%) is comparable to that expected from differential reddening alone, and so we tentatively conclude that the subtraction residuals can be explained largely as a consequence of variable extinction, and partly due to the presence of the He II line in the continuum bandpass. This could be tested by repeating the observations but selecting a continuum filter blueward of Hβ. The subtraction would then produce residuals in the reverse sense of those shown here. Furthermore, an extinction map could be generated from the ratio of an Hβ image to an Hα image to the residuals.

Measurement of the stellar magnitude can be performed using profile fitting techniques as described by Stetson (1987), or by simulated concentric aperture photometry (Adams *et al.* 1980). Since the dominant source of error is the background estimate, the simpler approach of aperture photometry is adequate. The implementation of the technique derives the background estimate from an aperture concentric with the star center and includes a correction for fractional pixels falling within the aperture. The background estimate is taken from the peak of the histogram of the background pixels, using an algorithm developed by H. Butcher for the KPNO Mountain Photometry Code.

To minimize the error which is introduced by the considerable background uncertainty, a small measuring aperture about an accurate center is required. The aperture used is 2 pixels in radius which corresponds to 1″.54 (3″.08 in diameter). Naturally, some light from the star is discarded as a result, and so nine bright stars in the field are measured through this aperture and a large 14″ diameter aperture to derive the aperture correction. This correction is 0.20 ± 0.01 mag. An additional correction must be added to account for light lost during the subtraction of the Hβ image which includes a small continuum contribution. This correction is derived from the same nine bright stars and is found to be 0.03 ± 0.01 mag. We have ignored the second-order effect arising from differences in the stellar temperatures between the field stars and the hot central star in this correction.

Transfer to a standard system is achieved by reference to the stars Hiltner 102, Feige 15, and G191B2B observed on the same night as NGC 7027. The monochromatic magnitudes given by Barnes and Hayes (1984) at $\lambda5263$ should be a good approximation to a magnitude at the filter central wavelength of $\lambda5279$. Agreement among the three standards is better than 0.05 mag. An additional correction is required to transform from the monochromatic magnitude at $\lambda5263$ to a Johnson V magnitude. For a reddened hot star, this correction is nearly zero, but depending on the spectrum of the star, may be as great as 0.1 mag, in the sense that V is brighter than m_{5263}. We adopt $m_{5263} - m_v = 0.05 \pm 0.05$.

The formal error in the measurement of the central star due to the background uncertainty is 0.25 mag. This clearly dominates the photon statistics which would predict an error well below 0.01 mag. After transforming to the Johnson system, and applying all corrections, we calculate $m_v = 16.32 \pm 0.35$, where the quoted uncertainty is conservatively computed by a simple addition of all the formal errors noted above.

An additional limit may be placed on this result by setting the underlying background level to zero. This predicts a bright limit of $m_v > 15.6$.

The photometry may also be performed by scaling the stellar profile to that of a nearby uncontaminated star. This is the essence of a point spread function fitting technique. Using this method, the calculated magnitude is $m_v = 16.24$. The scaled profile of a nearby star is shown overlaid on the profile of the central star in Figure 3, where the vertical bars represent different scale factors of ± 0.3 mag. Also shown in Figure 3 is the profile needed to scale the magnitude to 19.4 as reported by

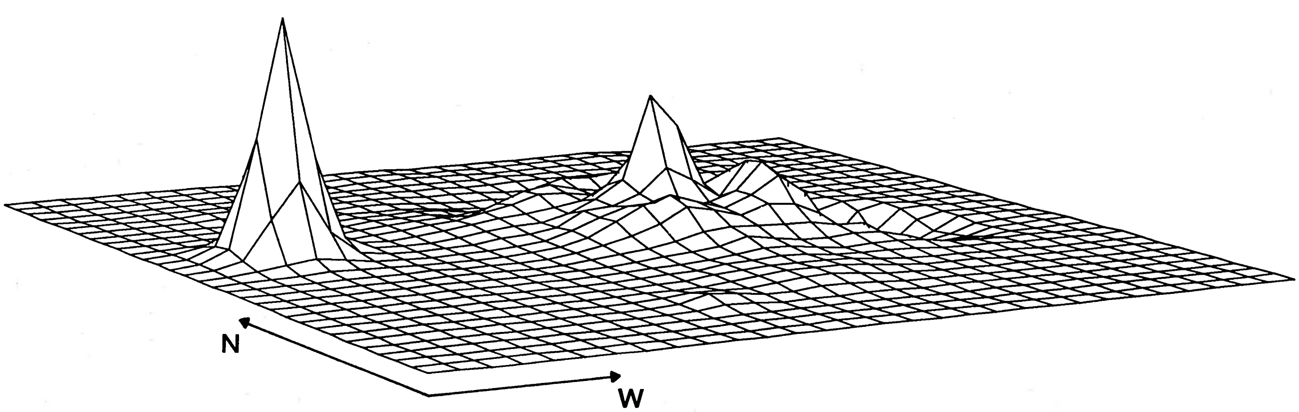

FIG. 4.—A surface rendition of Fig. 2. The magnitude of the residuals relative to the central star is more easily evaluated than in Fig. 2.

Atherton *et al.* (1979). A star this faint is clearly excluded by the observations.

III. DISCUSSION

The position of the central star is 10".35 west and 0".19 north of the nearby star visible in Figures 1, 2, and 4. This coincides within 1" of the position indicated by Harlan and Miller (1979), and confirms their positional estimate and identification. Atherton *et al.* (1979) report a stellar object at a position 2" east of the nebula peak. The central star candidate identified here has an offset relative to this peak of 3".14 east, and 0".55 north. This is in reasonable agreement for an offset from a nonstellar reference to confirm their identification as the central star of NGC 7027.

The disagreement among magnitude estimates would at first glance be somewhat disturbing since they extend over 5 mag. However, the considerable background estimate uncertainty combined with its rapid spatial variability near the central star indicate that an unsubtracted image cannot yield an accurate magnitude.

Given that $m_v = 16.32$, then the predicted central star temperature is 180,000 K, as computed by Shaw and Kaler (1982); this places the central star in an evolutionary diagram (cf. Wood and Faulkner 1986) at a mass of at least 0.65 $M_\odot$. A luminosity would constrain the mass estimates much better, but this requires a good estimate of the distance.

Distance estimates to NGC 7027 include 178 pc (Daub 1982) to 1500 pc (Pottasch *et al.* 1982). Recently, Masson (1986) derived a distance of 940 pc from radio expansion measurements. Jacoby and Lesser (1981) suggested using brightest extragalactic planetary nebulae to calibrate the [O III] λ5007 flux in order to place upper limits on the distances to other nebulae. Pottasch *et al.* (1982) used this concept with the Hβ flux to derive an upper limit near 1 kpc. Using the Hβ flux (7.64×10^{-14}) and reddening ($c = 1.37$) from Shaw and Kaler (1982), the ratio of [O III] to Hβ (13.14) from Kaler (1976), and the [O III] flux maximum (1.34×10^{-14} at 1 Mpc) from Jacoby and Lesser (1981), we calculate an upper limit of 800 pc for the distance. We therefore adopt a distance of 900 ± 200 pc to investigate the luminosity. Note that a distance as great as 1500 pc would imply an [O III] luminosity 3 times greater than any other Local Group planetary.

Assuming the central star can be represented by a hot blackbody at 180,000 K, then $m_v = 16.32$ and a distance of 900 pc implies a radius of 0.072 $R_\odot$ and a luminosity of 4900 $L_\odot$. Placing the temperature and luminosity in the evolutionary diagrams presented by Wood and Faulkner (1986) requires the central star mass to be near 0.65 $M_\odot$ if on a hydrogen-burning track, or near 0.7 $M_\odot$ if on a helium-burning track. This leads to an evolutionary age of 2000–3000 years, in qualitative agreement with a kinematic age of about 1000 years (Pottasch 1981). If the central star were as massive as 1 $M_\odot$ (Tylenda 1984) which is implied by observations yielding visual magnitudes fainter than 19, then the evolutionary age would be far too short. Thus the age discrepancy of a factor of 30 reported by Pottasch (1981) for NGC 7027 can be reconciled by an underestimate in the brightness of the central star by Atherton *et al.* (1979).

IV. CONCLUSION

An unambiguous identification and a picture of the central star of NGC 7027 is presented. The improvement in identification methods is made possible by CCD detectors having excellent linearity and dynamic range. The central star is found to have $m_v = 16.3$ which results in a star having moderate mass ($< 0.7\ M_\odot$) rather than one having high mass ($> 0.8\ M_\odot$).

The technique used to identify the star and render the data useful for a magnitude measurement is applicable to other stars in dense nebulae, such as NGC 2440, another candidate for having a massive central star (Atherton, Reay, and Pottasch 1986; Tylenda 1984). Observations by Atherton, Reay, and Pottasch (1986) suggest a faint star in the visual ($M_v = 18.9$) which leads to high temperature and mass estimates. By comparison Heap (1987) uses *IUE* spectra to detect the central star in the ultraviolet and predicts $M_v = 17.8$ indicative of a moderately hot star having a mass of 0.62 $M_\odot$. High-quality CCD observations can verify which of these investigators is correct.

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Notes added in proof.—N. A. Walton (private communications) reports the value of $m_v = 17.7$ given by Walton *et al.* (1988) is actually an observed magnitude rather than unreddened. A recent preprint by Walton, Pottasch, Reay, and Taylor revises that value to 17.0.

S. R. Heap and T. Hintzen (private communications) report a recent determination of $m_v = 16.19$ for the central star of NGC 7027 using a technique comparable to that described here.

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