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THE ABSOLUTE Hβ FLUX FROM NGC 7027

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ABSTRACT

We find the value of log $F(\mathrm{H}\beta)$ for NGC 7027 to be -10.12 ± 0.01 from a combination of new interference filter measurements and older independent determinations, which is 18% higher than the current standard value from Miller and Mathews. Substitution of the new flux in previous analyses yields an electron temperature from the Balmer continuum of $15{,}000 \pm 2500$ K, and an Hβ extinction of $c = 1.36 \pm 0.05$ from the radio flux density. The latter now agrees with the optical value of 1.37 ± 0.02, implying that the ratio of total to selective absorption is standard, at 3. The slope of the continuum in the optical now agrees better with theoretical prediction, although there is still an anomaly in the infrared. The hydrogen and He II Zanstra temperatures are equal at 180,000 K for a hypothetical central star at $m_v = 16.3$, which is too faint to be detected by the measurements discussed here.

Subject headings: interstellar: matter — nebulae: individual — nebulae: planetary — spectrophotometry

I. INTRODUCTION

NGC 7027 (PK 84−3°1) is the most heavily observed of the planetary nebulae. Despite its rather unusual nature (extremely high excitation and no well-defined central star), it has become a standard object, and its well-documented spectrum frequently serves as a reference against which other planetaries are compared.

Several investigators have measured the absolute Hβ flux from NGC 7027 during the last two decades. The most recent measurement, by Miller and Mathews (1972; hereafter MM), revised downward by nearly 20% the measured value of 7.59×10^{-11} adopted by Collins, Daub, and O'Dell (1961), based upon measurements by Capriotti and Daub (1960) and Liller (1955). (Note: in this discussion the Hβ flux includes the contaminating He II Pickering 8 line, which is about 2% of the strength of Hβ alone; see Kaler *et al.* 1976.) Kaler (1978) noted that the MM flux was inconsistent with Barker's (1978) fluxes of other planetaries when NGC 7027 was used as a standard calibration source. Good agreement was obtained, however, when the Collins, Daub, and O'Dell value was adopted.

Because of its importance in numerous investigations, and as an absolute standard, we have remeasured the absolute flux with carefully calibrated interference filters in order to resolve the inconsistency. This measurement was combined with earlier values, corrected to the modern stellar absolute standardization, and with an observed value obtained by using Barker's (1978) measurements as calibration standards. The final mean result is 18% higher than MM's value.

II. THE OBSERVATIONS

We measured the Hβ flux from NGC 7027 with the University of Illinois 1 m Cassegrain reflector at Prairie Observatory (see Kaler 1978). Four interference transmission filters were used: two with peak transmission near λ4861, and one each at λ5500 and λ4428 which were used to subtract the nebular continuum. Careful tracings of the filter transmission functions were made at a known temperature with a Cary 219 spectrometer. The temperature dependence of the filters was then removed from the observations, assuming a shift in effective wavelength of +0.2 Å per degree Celsius, as per the manufacturer's specifications.

We use 55 Cyg and BD +28°4211 as calibration standards. The flux distribution of 55 Cyg was originally calibrated by Kaler (1976*a*) on η UMa (from Wolff, Kuhi, and Hayes 1968) and BD +28°4211 (from Stone 1974). We rechecked the fluxes of 55 Cyg, including the effect of the Hβ absorption line, against both new and old observations of the BD star, where we allowed for the ambient filter temperature, and redetermined the equivalent width of the weak Hβ line in BD +28°4211 by observing with both the wide and narrow Hβ filters. We then placed the observed fluxes on the Hayes (1970) system, with absolute calibration by Oke and Schild (1970); the relevant parameters for α Lyr are:

$$F(\lambda 5556) = 3.36 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$$

$$F(\lambda 4861)/F(\lambda 5556) = 1.466.$$

TABLE 1

THE ABSOLUTE FLUX OF Hβ FROM NGC 7027

Reference	Log [F(Hβ + He II Pi8)][a]
Absolute filter calibration	−10.10±0.01
Barker calibration	−10.10±0.02
Capriotti and Daub 1960	−10.13±0.02
Peimbert and Torres-Peimbert 1971 ...	−10.14±0.02
Miller and Mathews 1972	−10.19±0.02
Mean value[b]	−10.12±0.01

[a]Multiply fluxes by 0.98 to obtain absolute Hβ (see § I).
[b]Excluding Miller and Mathews 1972.

The measured flux for NGC 7027 presented in the first row of Table 1 is the unweighted average of 16 nights' observations taken over 9 years from 1972 to 1980; the error quoted represents the mean error of the mean for these data. The observations were corrected for the temperature variation of the filters and radial velocity. Plots of the final individual Hβ fluxes against both time and temperature show no systematic variations, revealing the stability of the system.

Our second independent approach was to employ Barker's (1978) fluxes as a standard system to calibrate the Hβ filter. Kaler's (1976*a*, 1978) Hβ fluxes for nine planetaries observed in common with Barker, corrected for effects of temperature and radial velocity, allowed us to establish a mean relative scale factor between the two data sets with a deviation of about 2 percent. The 9 year's-worth of observations of NGC 7027, again corrected for temperature, were then placed on this scale. The resulting mean flux, presented in the second row of Table 1, agrees with the new Hβ flux derived from the absolute filter calibration. The error is the combination of the observational and scaling uncertainties.

Finally, we recalibrated the earlier fluxes of Capriotti and Daub (1960) and Peimbert and Torres-Peimbert (1971). The Capriotti and Daub observations were originally calibrated using one or more of a set of seven consistent standard stars. The flux they adopted for Vega at λ4861 was 5.17×10^{-9} ergs cm^{-2} s^{-1}, based upon the measured flux from the Sun at λ5560, the V magnitude of Vega from Johnson and Morgan (1953) and Johnson and Harris (1954), and monochromatic magnitudes from Code (1960). The Peimbert and Torres-Peimbert result used the flux for Vega at λ5480 from Code (1960) and the monochromatic magnitudes from Hayes (1970). Recalibration to the Hayes (1970) and Oke and Schild (1970) standard system simply required multiplication of the above fluxes by the appropriate scale factors.

The precise agreement between the absolute filter calibration and the Barker calibration may be misleading, since both employed the same filter set and could still contain unaccounted-for systematic effects. It is therefore preferable to average a variety of independent measurements. Since the impetus for this paper was the disagreement between the Capriotti and Daub and the MM values, and since our new results agree much more closely with the former, we chose to average all the values in Table 1 except for MM's. We treated our two new values as separate independent measurements, weighted equally. The final mean result for the Hβ (plus He II Pickering 8) flux from NGC 7027 is $(7.64\pm0.18)\times10^{-11}$ ergs cm^{-2} s^{-1}, or log F(Hβ) = −10.12±0.01.

III. IMPLICATIONS

This new Hβ flux allows us to reexamine the fit between the observed and theoretical nebular continuum, to improve and reconcile earlier values of electron temperature and extinction, and to make some comments about the central star.

a) *Electron Temperature*

Kaler (1976*b*) derived $T_e = 11{,}300\pm1300$ K from interference filter measurements of the Balmer continuum, MM's Hβ flux, and the theoretical emission rates given by Brocklehurst (1971, 1972) and Brown and Mathews (1970). The increase in the Hβ flux raises this value to 15,000±2500 K for the same optically derived value of extinction, $c = 1.37$. This value is close to that found by MM from the best theoretical continuum fit to their self-consistent data and is still in agreement with Kaler *et al.*'s (1976) value of 13,500 (+6000, −2500) K derived from the photographically observed Balmer continuum.

b) *Extinction Constant*

A number of authors, including MM, Kaler *et al.* (1976), and Seaton (1979), have noted that the extinction derived from the radio continuum/Hβ flux ratio is higher than that derived optically, implying a ratio of total to selective extinction, R, significantly greater than 3. Kaler *et al.* (1976) give c(radio) = 1.50±0.02, based on $T_e = 11{,}500$ K and MM's Hβ flux. Our new Hβ flux and the resulting $T_e = 15{,}000\pm2500$ K yields a lower value for the radio-derived extinction, $c = 1.36\pm0.05$, in agreement with the optical value of 1.37±0.02 and consistent with the usual assumption of $R = 3$.

c) *Continuum Fit*

Both MM and Kaler (1976*b*) tried to fit the theoretically predicted and observed continua. In both cases, the observed slope in the optical toward higher frequencies is greater than the theoretical. In Figure 1 we show a new fit to the data presented by Kaler (1976*b*), modified only for our new Hβ flux. The best fit for $c = 1.37$ was obtained by eye estimate for $T_e = 15{,}500$ K, close to the value calculated above, and x (the probability of a two-photon decay following a recombination; see Brown and Mathews 1970) = 0.10. The slope in the optical is very satisfactory, but the theory overpredicts

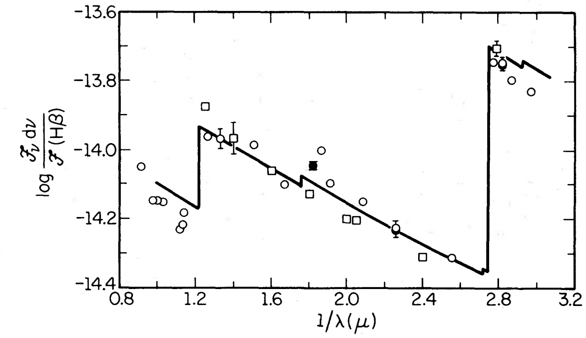

FIG. 1.—The continuous spectrum of NGC 7027. The observed points, corrected for $c = 1.37$, are taken from Kaler 1976*b*, modified for the new Hβ flux. *Open circles*: sample points from Miller and Mathews 1972; *boxes*: Danziger and Goad 1973; *closed circles*: original measurements in Kaler 1976*b*. The line is the theoretical curve for $T_e = 15500$, $x = 0.10$.

in the infrared, and to a smaller degree in the ultraviolet. It also overpredicts the longer wavelength measurements made by Danziger and Goad (1973) indicated by Kaler (1976*b*) but not shown here. A combination of systematic errors in the observation and deviation from the standard Whitford (1958) reddening function could be responsible. It is disconcerting that while our new Hβ flux is 18% higher than MM's, the Kaler (1976*b*) and MM optical continuum fluxes on the whole agree with one another. MM claim a $\pm 20\%$ error for their individual continuum measurements, however, which may mask a systematic difference. Raising MM's continuum fluxes consistently by the same 18% brings the infrared and ultraviolet into better agreement with the theoretical curve, but then the optical points become too high, and we still have the longer wavelength measurements by Danziger and Goad (1973) to contend with. On the whole, the agreement between theory and observation appears to be improved, but it is still not perfect.

d) *The Central Star*

The central star has never been unambiguously detected. Harlan and Miller (1979) identified a "starlike image" in a continuum photograph as a possible candidate, with visual magnitude $\approx 15 \pm 1$. Atherton *et al.* (1979) did the same and suggested $m_v = 19.4 \pm 1$. We adopted $F(\lambda 4686) = 0.42 F(\lambda 4861)$ from Kaler *et al.* (1976), our new Hβ flux, and $c = 1.37$, and calculated hydrogen and He II Zanstra temperatures (see Harman and Seaton 1966) for a progression of central star magnitudes. T_z(H) will equal T_z(He II) for a blackbody if the nebula is optically thick at all Lyman wavelengths, a condition that might be expected for a compact nebula of such high density. Equality occurs at $m_v = 16.4$ and $T_z = 180{,}000$ K. At that magnitude a hypothetical central star makes less than a 2% difference in the continuum at *B* and would be undetectable in our total photometry. This simple analysis must be used with caution, since it could easily be confused by deviations in the stellar spectrum from a blackbody and internal dust. Nevertheless, a temperature for the central star of 180,000 K, one of the highest known, makes at least a useful working excitation temperature for the object.

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REFERENCES

Atherton, P. D., Hicks, T. R., Reay, N. K., Robinson, G. J., and Worswick, S. P. 1979, *Ap. J.*, **232**, 786.
Barker, T. 1978, *Ap. J.*, **219**, 914.
Brocklehurst, M. 1971, *M.N.R.A.S.*, **153**, 471.
______. 1972, *M.N.R.A.S.*, **159**, 211.
Brown, R. L., and Mathews, W. G. 1970, *Ap. J.*, **160**, 939.
Capriotti, E. R., and Daub, C. T. 1960, *Ap. J.*, **132**, 677.
Code, A. D. 1960, in *Stars and Stellar Systems*, Vol. **6**, *Stellar Atmospheres*, ed. J. Greenstein (Chicago: University of Chicago Press), p. 50.
Collins, G. W., II, Daub, C. T., and O'Dell, C. R. 1961, *Ap. J.*, **133**, 471.
Danziger, I. I., and Goad, L. E. 1973, *Mém. Soc. Roy. Liège*, 6e Sér., **5**, 153.
Harlan, E. A., and Miller, J. S. 1979, *Pub. A.S.P.*, **91**, 168.
Harman, R. J., and Seaton, M. J. 1966, *M.N.R.A.S.*, **132**, 15.
Hayes, D. S. 1970, *Ap. J.*, **159**, 165.
Johnson, H. L., and Harris, D. L. 1954, *Ap. J.*, **120**, 196.
Johnson, H. L., and Morgan, W. W. 1953, *Ap. J.*, **117**, 313.
Kaler, J. B. 1976*a*, *Ap. J.*, **210**, 113.
______. 1976*b*, *Ap. Letters*, **17**, 163.
______. 1978, *Ap. J.*, **226**, 947.
Kaler, J. B., Aller, L. H., Czyzak, S. J., and Epps, H. W. 1976, *Ap. J. Suppl.*, **31**, 163.
Liller, W. 1955, *Ap. J.*, **122**, 240.
Miller, J. S., and Mathews, W. G. 1972, *Ap. J.*, **172**, 593 (MM).
Oke, J. B., and Schild, R. E. 1970, *Ap. J.*, **161**, 1015.
Peimbert, M., and Torres-Peimbert, S. 1971, *Bol. Obs. Tonantzintla y Tacubaya*, **6**, 21.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 785.
Stone, R. P. S. 1974, *Ap. J.*, **193**, 135.
Whitford, A. E. 1958, *A.J.*, **63**, 201.
Wolff, S. C., Kuhi, L. V., and Hayes, D. 1968, *Ap. J.*, **158**, 871.

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