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OBSERVATIONS OF PLANETARY NEBULAE AT 1.65 TO 3.4 MICRONS

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ABSTRACT

Photometric measurements at 2.2 μ of 15 planetary nebulae are presented, along with measurements of 12 at 1.65 μ and seven at 3.4 μ. The measurements agree with the predicted thermal emission from ionized hydrogen and helium except for four nebulae. IC 418 and BD+30°3639 are brighter than predicted at all three wavelengths, and NGC 40 shows excesses at 1.65 and 2.2 μ, but was not measured at 3.4 μ. NGC 7027 shows an excess only at 3.4 μ. All the excesses are interpreted in terms of emission from dust distributed throughout or surrounding the nebulae. Dust temperatures as high as 1000° K are needed to explain the excess at 1.65 μ.

I. INTRODUCTION

Many planetary and diffuse nebulae are known to radiate more energy between 5 and 13 μ than can be accounted for by free-free emission alone (Gillett, Low, and Stein 1967; Woolf 1969; Gillett and Stein 1969, 1970; Hilgeman 1969; Neugebauer and Garmire 1970; Gillett, Knacke, and Stein 1971). The measurements indicate that different objects have different energy distributions. Hilgeman (1969) gives evidence that there is an excess at 2.2 μ and shorter wavelengths from the Orion Nebula. The present series of observations was undertaken to see if there is a 1–2.5-μ excess among planetary nebulae, and to determine the energy distribution of a large number of planetaries at wavelengths where interstellar extinction is small.

We have observed 16 planetary nebulae, detecting 12 at 1.65 μ, 15 at 2.2 μ, and seven at 3.4 μ with signals greater than 2 standard deviations. Very few other observations of planetaries at these wavelengths have been reported, but the present results are in good agreement with measurements of NGC 6572 and BD+30°3639 at 3.6 μ by Gillett and Stein (1970) and with measurements of NGC 7027 and IC 418 at 2.2 μ by Hilgeman (1969).

II. THE OBSERVATIONS

Most of the observations were made with the Smithsonian Astrophysical Observatory infrared photometer mounted at the Cassegrain foci of the Kitt Peak 36-inch (91 cm), the Agassiz Station 61-inch (155 cm), and the Mount Hopkins 60-inch (152 cm) telescopes. Several observations were made with the California Institute of Technology infrared photometer mounted at the Cassegrain foci of the Mount Wilson 60- and 100-inch (152 and 254 cm) telescopes.

The infrared fluxes from the planetaries were generally quite weak, so that between 10 and 72 10-second integrations were required on each object at each wavelength to give a signal-to-noise ratio greater than 5. The observations were calibrated by observing standard stars of Johnson *et al.* (1966), before and after observing each nebula.

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The standard stars were chosen as near as possible to the nebulae measured. The absolute calibration of Becklin (1968) has been used to reduce the observed apparent magnitudes to flux density outside the Earth's atmosphere.

The planetary nebulae observed range from about 5 to about 40 seconds of arc in diameter (Perek and Kohoutek 1967). Diaphragms were chosen to be larger than the visual diameter of the nebula; therefore, these observations should be directly comparable to radio observations of total flux.

Table 1 gives the photometric observations at 1.65 μ ($\Delta\lambda = 0.3\ \mu$), 2.2 μ ($\Delta\lambda = 0.4\ \mu$), and 3.4 μ ($\Delta\lambda = 0.6\ \mu$). Table 2 gives the average of all the observations of each ob-

TABLE 1

FLUX DENSITIES MEASURED ON INDIVIDUAL NIGHTS

Object	Date and Telescope*	Aperture Diameter (arc sec)	Observed Flux Density ($\times 10^{-26}$ W m^{-2} Hz^{-1}) 1.65 μ	2.2 μ	3.4 μ
NGC 40	I	47	0.15 ±0.02	0.19 ±0.02	<0.43
NGC 1535	I	32	<0.31	...	<0.51
NGC 2392	E	66	<0.22	0.12 ±0.03	...
NGC 3242	E	33	...	0.19 ±0.04	...
	E	66	0.22 ±0.11	...	...
NGC 6210	E	33	...	0.16 ±0.04	<0.53
	G	27	...	0.14 ±0.02	<0.25
	G	40	...	0.11 ±0.02	...
NGC 6369	E	33	0.23 ±0.04	0.37 ±0.07	0.68±0.20
NGC 6543	A	48	...	0.34 ±0.08	...
	E	33	...	0.23 ±0.05	...
	E	33	0.23 ±0.03	0.25 ±0.03	<0.83
	G	27	...	0.31 ±0.02	0.40±0.11
NGC 6572	E	33	0.18 ±0.04	0.39 ±0.04	...
	E	33	0.36 ±0.09	0.42 ±0.06	0.27±0.22
	G	27	...	0.43 ±0.03	0.39±0.07
	G	27	...	0.38 ±0.03	<0.43
	G	40	...	0.38 ±0.04	...
	H	27	0.32 ±0.03	0.40 ±0.03	0.47±0.08
NGC 6826	F	34	...	0.14 ±0.03	<0.28
	H	27	0.13 ±0.02	0.17 ±0.02	...
NGC 7009	A	48	...	0.21 ±0.05	...
	B	48	0.16 ±0.03	0.13 ±0.05	...
	H	40	...	0.21 ±0.02	0.23±0.13
NGC 7026	H	27	<0.06	0.058±0.016	...
NGC 7027	C	16	...	1.90 ±0.30	7.70±0.80
	H	27	1.04 ±0.07	1.78 ±0.13	6.60±0.50
NGC 7354	H	27	0.053±0.014	0.091±0.011	...
	H	40	...	0.106±0.014	...
NGC 7662	A	48	...	0.22 ±0.06	...
	H	27	0.10 ±0.02	0.15 ±0.02	<0.38
	H	27	0.16 ±0.02	...	...
	H	27	0.12 ±0.02	...	0.22±0.07
	H	27	0.14 ±0.02	0.16 ±0.02	0.78±0.35
IC 418	D	27	0.56 ±0.17	0.97 ±0.20	1.15±0.25
	E	33	0.69 ±0.20	1.42 ±0.15	0.95±0.40
	I	32	0.67 ±0.05	1.13 ±0.08	1.61±0.11
	J	20	...	...	1.66±0.32
BD+30°3639	G	27	...	0.55 ±0.04	1.62±0.11
	H	27	0.32 ±0.03	0.63 ±0.05	...

* Key to date and telescope: A = Mount Wilson 60-inch, 1965 August. B = Mount Wilson 60-inch, 1966 August. C = Mount Wilson 60-inch, 1969 June. D = Agassiz Station 61-inch, 1969 December. E = Kitt Peak 36-inch #2, 1970 March. F = Kitt Peak 36-inch #1, 1970 May. G = Agassiz Station 61-inch, 1970 July. H = Agassiz Station 61-inch, 1970 August. I = Mount Hopkins 60-inch, 1970 September–October. J = Mount Wilson 100-inch, 1971 September.

TABLE 2

OBSERVATIONS AVERAGED AND CORRECTED FOR INTERSTELLAR EXTINCTION

Object	Reddening Coefficients (decimal logarithms)	Corrected Flux Density ($\times 10^{-26}$ W m^{-2} Hz^{-1})		
		1.65 μ	2.2 μ	3.4 μ
NGC 40........	0.97	0.20±0.02	0.22±0.02	<0.47
NGC 1535......	0.13	<0.32	...	<0.52
NGC 2392......	0.41	<0.25	0.13±0.03	...
NGC 3242......	0.33	0.24±0.12	0.20±0.04	...
NGC 6210......	0.14	...	0.13±0.02	<0.25
NGC 6369......	2.20	0.43±0.07	0.54±0.10	0.83±0.24
NGC 6543......	0.17	0.24±0.03	0.29±0.02	0.41±0.11
NGC 6572......	0.56	0.39±0.04	0.44±0.03	0.42±0.06
NGC 6826......	0.17	0.14±0.02	0.16±0.02	<0.29
NGC 7009......	0.24	0.17±0.03	0.20±0.02	0.23±0.13
NGC 7026......	0.99	<0.08	0.07±0.02	...
NGC 7027......	1.57	1.65±0.08	2.41±0.08	8.10±0.31
NGC 7354......	1.96	0.09±0.03	0.14±0.02	...
NGC 7662......	0.53	0.15±0.01	0.18±0.02	0.33±0.09
IC 418.........	0.33	0.72±0.06	1.25±0.08	1.47±0.11
BD+30°3639...	0.39	0.36±0.03	0.63±0.04	1.68±0.11

ject, corrected for interstellar extinction. The extinction corrections at the wavelength of Hβ are also listed in table 2; they have been taken from Cahn and Kaler (1971) except as noted below.[1] The reddening curve used is van de Hulst's curve 15 (Johnson 1968), which gives the following values for the extinction coefficient relative to that at Hβ: 0.123 at 1.65 μ, 0.075 at 2.2 μ, and 0.039 at 3.4 μ. In all but three cases, the correction for extinction at 2.2 μ is less than 20 percent; the maximum correction at this wavelength is 46 percent.

In addition to the observations reported in tables 1 and 2, IC 418 and BD+30°3639 were observed with the 100-inch telescope at Mount Wilson. Observations of each object at 2.2 μ were made with three different apertures. In each case the aperture was centered on the central star of the nebula. Because the nebulae are circular in appearance, there should be no effect from asymmetry. The apertures, fluxes, and errors are shown in table 3.

The errors quoted in tables 1, 2, and 3 are standard errors and include the statistical uncertainty of the observations of the nebulae and of the standard stars. Systematic errors, errors in the absolute calibration, and errors in the interstellar-extinction correction are not included. The fluxes measured on different nights and with different telescopes agree within the quoted errors.

III. DISCUSSION

It is expected that a significant fraction of the radiation from planetary nebulae at these wavelengths will be thermal emission from ionized hydrogen and helium. Therefore, the expected thermal emission of the nebulae was calculated by using available radio observations (Higgs 1970) and recombination theory to give the ratio of infrared

[1] Cahn and Kaler (1971) derive the extinction at Hβ by comparing the flux in the Hβ line with an adopted 3-GHz radio flux. Because Cahn and Kaler did not use any radio observations at frequencies higher than 5 GHz, and because some nebulae are optically thick at 5 GHz and lower frequencies, the extinction derived may be too low. A new estimate of the equivalent 3-GHz flux was therefore made for the objects NGC 6572, NGC 7027, and BD+30°3639 by using all the radio observations listed by Higgs (1970) at frequencies at or above a minimum frequency.

TABLE 3

2.2-μ FLUX FROM IC 418 AND BD+30°3639 AS A FUNCTION OF APERTURE SIZE

Object	Aperture (arc seconds)	Measured Flux ($\times 10^{-26}$ W m^{-2} Hz^{-1})
IC 418.........	5.0	0.11±0.01
	9.7	0.37±0.02
	19.5	0.83±0.04
BD+30°3639...	4.1	0.21±0.01
7.0............	7.0	0.45±0.02
	15.2	0.55±0.03

to radio flux. Details of the calculation are given in the Appendix, and the results are given in table 4 in the form of predicted infrared fluxes from each of the nebulae measured.

All but four of the nebulae measured show agreement between the predicted and observed fluxes, as can be seen from table 4. This confirms the idea that 1.65–3.4-μ radiation from most planetary nebulae comes from thermal emission from ionized hydrogen and helium. The excess radiation from the other four nebulae (NGC 7027, IC 418, BD+30°3639, and NGC 40) is discussed below.

NGC 7027 shows excess radiation at 3.4 μ but not at shorter wavelengths. Krishna Swamy and O'Dell (1968) have explained the 5–13-μ excess observed in NGC 7027 (Gillett *et al.* 1967) by emission from graphite dust at a temperature of 200° K. However, the present 3.4-μ measurement of NGC 7027 falls considerably above an extrapolation of their theoretical curve. In fact, no single-temperature model assuming a power-law emissivity function will fit all the data from 3.4 to 12.5 μ. Figure 1 shows that an artificial two-temperature model does fit the observations. In this model, the radia-

TABLE 4

PREDICTED FLUX DENSITY* AND EXCESS

OBJECT	MINIMUM FREQUENCY (GHz)	1.65 μ		2.2 μ		3.4 μ	
		Predicted	Excess	Predicted	Excess	Predicted	Excess
NGC 40.......	5.0	0.12±0.01	0.08±0.02	0.14±0.01	0.08±0.02	...	...
NGC 2392.....	5.0	...	...	0.09±0.01	0.04±0.03	...	...
NGC 3242.....	5.0	0.21±0.01	0.03±0.12	0.24±0.02	−0.04±0.04	...	...
NGC 6210.....	5.0	...	...	0.11±0.01	0.02±0.02	...	...
NGC 6369.....	5.0	0.53±0.03	−0.10±0.08	0.61±0.04	−0.07±0.11	0.51±0.03	0.32±0.24
NGC 6543.....	5.0	0.24±0.02	0.00±0.03	0.28±0.02	0.01±0.03	0.24±0.02	0.17±0.11
NGC 6572.....	8.0	0.37±0.03	0.02±0.05	0.44±0.03	0.00±0.04	0.37±0.02	0.05±0.06
NGC 6826.....	5.0	0.12±0.01	0.02±0.02	0.14±0.01	0.02±0.02	...	...
NGC 7009.....	5.0	0.20±0.01	−0.03±0.03	0.23±0.02	−0.03±0.03	...	...
NGC 7026.....	6.63	...	...	0.09±0.01	−0.02±0.02	...	...
NGC 7027.....	8.0	1.89±0.10	−0.24±0.13	2.19±0.12	0.22±0.14	1.84±0.10	6.26±0.33
NGC 7354.....	5.0	0.16±0.01	−0.07±0.03	0.19±0.02	−0.05±0.03	...	...
NGC 7662.....	5.0	0.19±0.01	−0.04±0.02	0.22±0.02	−0.04±0.03	0.19±0.01	0.14±0.09
IC 418........	5.0	0.46±0.03	0.26±0.07	0.54±0.03	0.71±0.09	0.45±0.03	1.02±0.11
BD+30°3639..	6.63	0.16±0.02	0.20±0.03	0.18±0.02	0.45±0.04	0.16±0.01	1.52±0.11

* In units of 10^{-26} W m^{-2} Hz^{-1}.

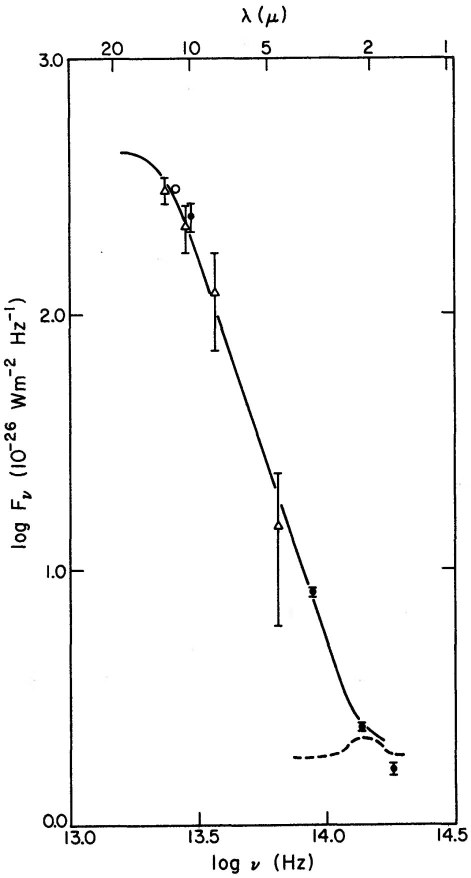

FIG. 1.—Observations of NGC 7027. *Points* refer to the present paper; *circle*, to Woolf (1969); *triangles*, to Gillett *et al.* (1967), whose 8–13-μ observations have been increased by a factor of 1.8 to agree with our observation and that of Woolf at 10 μ. *Dashed line*, the expected recombination radiation. *Solid line*, the sum of the recombination radiation, a component at 200° K, and a component at 500° K; the latter two components have emissivity proportional to λ^{-1}.

tion is the sum of the thermal emission from ionized hydrogen and helium, particle emission at a temperature of 200° K, and particle emission at a temperature of 500° K with an optical depth $\sim 10^{-3}$ times as large. While a two-temperature model is not physically realistic, it demonstrates that a distribution of particle temperatures between 200° and 500° K will fit the observations. It is not surprising that a range of dust temperatures exists in the nebulae, because smaller particles, which are less efficient emitters, should be hotter than larger particles.

In IC 418 and BD+30°3639 an excess is observed at 1.65 and 2.2 μ as well as at 3.4 μ. NGC 40 shows an excess at 1.65 and 2.2 μ but was not observed at 3.4 μ. Hilgeman (1969) attributed an apparent excess at 2.2 μ and shorter wavelengths in the Orion Nebula to scattering of starlight by dust. However, if the central stars of the planetary nebulae radiate as blackbodies with $T \geq 20{,}000°$ K, the flux from the photosphere of the star is 10 times too small for either direct emission or dust scattering to be important at these wavelengths. Line emission also seems unlikely because in IC 418 Hilgeman (1969) found only one line, the Bγ of H I between 2.0 and 2.4 μ. The equivalent width was 204 ± 90 Å, which represents much less energy than that in the continuum.

It thus appears that the most likely explanation of the 1.65- and 2.2-μ excesses is emission by dust. Table 5 shows the color temperatures calculated from the ratio of the

TABLE 5

COLOR TEMPERATURES FROM 1.65- AND 2.2-μ OBSERVATIONS

Object	$F_\nu(2.2\ \mu)/F_\nu(1.65\ \mu)$	T_c (° K)
NGC 40........	1.0±0.4	1460 (+630, −250)
IC 418.........	2.7±0.8	860 (+140, − 80)
BD+30°3639...	2.2±0.4	930 (+ 90, − 60)

2.2–1.65 μ excesses in NGC 40, BD+30°3639, and IC 418. The emissivity is assumed proportional to λ^{-2}; temperatures from 800° to over 1000° K are found.

Because the three nebulae with 2.2-μ excesses have relatively bright central stars of type WC (Perek and Kohoutek 1967), it might be thought that the hottest grains are very close to the central star of the nebula and are heated directly by stellar radiation instead of by Lα radiation scattered throughout or escaping from the nebula as discussed by Krishna Swamy and O'Dell (1968). The aperture dependence of the 2.2-μ flux from BD+30°3639 and IC 418 shown in table 3 demonstrates, however, that the excess radiation comes from the entire nebula—not just the region near the central star. If the radiation through the smallest aperture used is subtracted from the total radiation from the nebula, there is still twice as much radiation as is predicted from recombination. The observations of both nebulae are consistent with the source being at least as large as the optical nebula, and comparisons of table 1 and table 3 suggest that the 2.2-μ infrared source in IC 418 may be larger than 20″ in diameter, compared with the optical diameter of 12″ (O'Dell 1962).

It is interesting that NGC 6572 is known to have a large excess at 10 μ (Gillett and Stein 1970) but has no excess at 3.4 μ or shorter wavelengths. This indicates that the temperature of the dust in this object is below ~250° K.

NGC 7027, IC 418, and BD+30°3639 are among the planetary nebulae with the highest electron density (Kaler 1970) and therefore the highest radio surface brightness. These three nebulae also have the largest excesses at 1.65–3.4 μ. However, NGC 40 also has a large excess at 1.65 and 2.2 μ, but is much less dense than many planetaries that show no excess at these wavelengths. Observational selection may be partly responsible for some correlation between electron density and infrared excess, because the nebulae observed in this program were those with the largest radio fluxes among those planetaries less than about 40″ in diameter. For these reasons the present evidence does not establish a correlation between electron density and infrared excess.

IV. SUMMARY

The 1.65–3.4-μ radiation from most of the nebulae observed seems to be thermal emission from ionized hydrogen and helium. A minority of nebulae show an excess at one or more wavelengths; the energy distributions of the excesses are not all the same.

The excesses are interpreted as due to emission by dust. Dust temperatures in the range 200°–1000° K are found, and the dust is spread throughout the volume of the nebula and perhaps beyond. Presumably the dust is all heated by radiation in and escaping from the nebula, and the temperature of each grain depends on its size. The maximum temperature varies among the nebulae, which implies that the minimum grain size also varies.

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APPENDIX

Thermal emission from ionized gas includes free-free and free-bound emission from H II, He II, and He III, two-photon emission from the $2s$–$1s$ transition in H I, and a small contribution from hydrogen and helium transition lines. At wavelengths longer than 5 μ only the free-free radiation is important; free-bound emission becomes important at wavelengths shorter than 5 μ, and two-photon emission becomes significant at wavelengths shorter than 2 μ. Line emission remains small for the large bandpasses used here; Bγ may contribute $\sim$5 percent to the 2.2-μ flux.

The total thermal radiation in each of the three infrared bands observed and at several radio frequencies was calculated numerically from Kramers's formulae with infrared free-free Gaunt factors from Karzas and Latter (1962); all the processes mentioned above were included. Radio Gaunt factors were calculated from the formula given by Aller and Liller (1968). The free-bound Gaunt factor was taken as 1.0. The ratio of the infrared flux to the radio flux depends extremely weakly on temperature ($\propto T^{-1/7}$ in the worst case) and changes by less than 10 percent for $r \equiv N(\text{He III})/[N(\text{H II}) + N(\text{He II})]$ between 0.0 and 0.1. [The flux ratio is almost independent of $N(\text{He II})/N(\text{H II})$.] Thus with about 5 percent error we may take $T = 10{,}000°$ K, $r = 0.05$ for all nebulae, for which we find the ratio of the infrared flux to the 5-GHz radio flux to be 0.26 at 1.65 μ, 0.30 at 2.2 μ, and 0.26 at 3.4 μ, provided the nebula is optically thin both in the infrared and at 5 GHz.

Radio observations were taken from the unpublished catalog of Higgs (1970), which lists all radio observations of planetary nebulae published as of 1970 August, as well as many unpublished observations by Higgs. A predicted infrared flux and error were calculated for each radio observation at or above a minimum frequency chosen so that the nebula is optically thin at those frequencies. The predicted infrared flux given in table 4 is the weighted average of the predictions from each radio frequency. The errors listed include the errors of the radio observations and 5 percent estimated error in the numerical calculations. The 16.2-GHz observations of Ehman (1969) were reduced by 7 percent as he assumed too large a value for the flux from the standard source Cyg A (Dent 1971).

REFERENCES

Aller, L. H., and Liller, W. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 536.
Becklin, E. E. 1968, Ph.D. thesis, California Institute of Technology.
Cahn, J. H., and Kaler, J. B. 1971, *Ap. J. Suppl.*, **22**, 319.
Dent, C. 1971, private communication.
Ehman, J. R. 1969, Ph.D. thesis, University of Michigan.
Gillett, F. C., Knacke, R. F., and Stein, W. A. 1971, *Ap. J.* (*Letters*), **163**, L57.
Gillett, F. C., Low, F. J., and Stein, W. A. 1967, *Ap. J.* (*Letters*), **149**, L97.
Gillett, F. C., and Stein, W. A. 1969, *Ap. J.* (*Letters*), **155**, L97.
———. 1970, *Ap. J.*, **159**, 817.
Higgs, L. A. 1970, *Catalog of Radio Observations of Planetary Nebulae and Related Optical Data* (National Research Council of Canada, unpublished).
Hilgeman, T. 1969, Ph.D. thesis, California Institute of Technology.
Johnson, H. L. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 193.
Johnson, H. L., Mitchell, R. I., Iriarte, B., and Wisniewski, W. Z. 1966, *Comm. Lunar and Planetary Lab.*, **4**, 99.

Kaler, J. B. 1970, *Ap. J.*, **160**, 887.
Karzas, W. J., and Latter, R. 1962, *Ap. J. Suppl.*, **6**, 167.
Krishna Swamy, K. S., and O'Dell, C. R. 1968, *Ap. J.* (*Letters*), **151**, L61.
Neugebauer, G., and Garmire, G. 1970, *Ap. J.* (*Letters*), **161**, L91.
O'Dell, C. R. 1962, *Ap. J.*, **135**, 371.
Perek, L., and Kohoutek, L. 1967, *Catalog of Galactic Planetary Nebulae* (Prague: Academy of Sciences).
Woolf, N. J. 1969, *Ap. J.* (*Letters*), **157**, L37.