

INTERSTELLAR MATTER IN ELLIPTICAL NEBULAE

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ABSTRACT

Although the $\lambda 3727$ doublet is blended by internal motions in representative elliptical nebulae, it is possible to estimate the density of free electrons in the interstellar gas in these nebulae by observing the wave length of the blend. In NGC 1052, an elliptical with unusually strong emission lines, the measured wave length corresponds to an intensity ratio near the asymptotic low-density limit, and the conclusion is that the mean electron density in ionized regions of interstellar space in this galaxy is less than a few hundred per cubic centimeter. If hot blue stars were present in relative numbers similar to the population of the globular cluster M3, then these stars would provide enough ionization to produce all the observed line emission. Also enough interstellar matter would have resulted from stellar evolution alone to explain all the observed emission. It is possible, however, that a considerable fraction of the ionization is produced by energy supplied by the degradation of turbulent energy, and it is also possible that much of the interstellar matter was present from the original time of formation of the elliptical.

I. INTRODUCTION

In terms of the original two-population hypothesis put forward by Baade (1944), elliptical nebulae are composed of pure population II stars. Furthermore, population II systems do not contain interstellar dust (Baade 1951), and it might therefore be supposed that elliptical nebulae do not include any interstellar matter at all. This, however, is not correct; the statement applies only to dust, as is mostly clearly shown by the observations of the [O II] $\lambda 3727$ emission line.

The presence of this line in the spectrum of an elliptical nebula was first reported by Mayall (1936) for the case of the E3 galaxy NGC 1052. Mayall later (1939) investigated the occurrence of the $\lambda 3727$ emission line as a function of nebular type and found that the frequency of occurrence was greatest for late-type spirals and smallest for ellipticals, among which only one (NGC 1052) of the fourteen he had by then observed showed the line. The most recent and complete statistics are available in the red-shift catalogue of Humason, Mayall, and Sandage (1956) and have been summarized by Mayall (1958). Of a total of 82 E0–E7 nebulae for which Mount Wilson spectra were obtained sufficiently well exposed to show $\lambda 3727$ if present, 18 per cent did, in fact, show the emission line. For the Lick spectra, it may fairly be assumed that all the nebulae with velocities less than 10000 km/sec are bright enough so that well-exposed spectra were obtained, and, of a total of 36 E0–E7 nebulae in this velocity range, 14 per cent showed the line in emission. Thus both surveys indicate that a small, but by no means negligible, proportion of the ellipticals have [O II] $\lambda 3727$ in emission.

A certain fraction of the emission-line elliptical nebulae can be explained by extraneous circumstances; for instance, the nucleus of the E1 galaxy NGC 3226 is overlapped in projection by an outlying spiral arm of the Sb system NGC 3227, and in this case the reported $\lambda 3727$ emission in the elliptical may, in fact, come from the spiral. The majority of the cases, however, are isolated ellipticals or ellipticals with elliptical companions, and for these there is no doubt that the emission line is intrinsic to the nebula. Now the [O II] $\lambda 3727$ line can be observed in emission only from low-density ionized gas clouds, of which diffuse and planetary nebulae are the best-known examples in our Galaxy. Evidence presented in Section II shows that the gas density in at least one ellip-

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tical nebula is much lower than in typical planetaries, so that we can indeed identify the source of emission with interstellar matter. The present paper is devoted to a preliminary study of this interstellar matter in elliptical nebulae.

Section II describes an attempt to determine the mean density of the ionized interstellar matter, by observations of the $[O II] \lambda 3727$ line. Then Section III shows that the observed strength of this emission line is compatible with the idea that the interstellar matter is ionized by a relatively few hot blue stars, which could be expected to occur in an elliptical nebula. Furthermore, even if all the mass of the elliptical had once been concentrated into stars, the evolution of the brightest of these stars with consequent mass loss would have been enough to contribute to interstellar space the whole observed mass of ionized matter. Section IV discusses, in a preliminary way, the contribution to the ionization of kinetic energy of mass motion, degraded to heat; and a final summary concludes the paper.

II. OBSERVATIONS OF $\lambda 3727$ IN NGC 1052

The so-called $\lambda 3727$ line of $[O II]$ is actually a close doublet with a separation between its two components of 2.8 Å. The intensity ratio of these two components changes in a known way with the electron density, and hence the measurement of their relative strengths is a method for determining the density in nebulae in which the lines occur (Seaton 1954; Seaton and Osterbrock 1957). It is therefore natural to attempt to measure this intensity ratio in elliptical nebulae, and for this purpose spectrograms were taken, with the same equipment as that used to study the Crab Nebula at the 200 inch telescope (Osterbrock 1957), of a number of ellipticals known from the work of Humason, Mayall, and Sandage (1956) to have $\lambda 3727$ in emission. The spectrograms were taken with the nebulae held fixed on the slit of the spectrograph, and in each case they showed a broadened, inclined line. The inclination shows that the interstellar matter has a systematic velocity of rotation about the center of the nebula, while the broadening shows that a line of sight penetrates matter with a considerable range of velocities. The whole width to half-maximum of the $\lambda 3727$ emission line is, in each case, of the order of 8 Å or 600 km/sec, which is so much greater than the separation of the components that they are completely unresolved, and hence their intensity ratio cannot be measured directly.

However, it is clear that the apparent wave length of the $\lambda 3727$ blend depends on the intensity ratio, because, for instance, if one of the two components were infinitely strong, then the measured wave length would certainly be the same as the wave length of this component. We have therefore attempted, by measuring the wave length of the blend, to determine indirectly the intensity ratio. This scheme has been previously applied by Minkowski and Wilson (1956) to the Cygnus A radio source, as a check on the wave length and with an assumed electron density. In order to apply this method to an extragalactic nebula, it is necessary to determine its apparent radial velocity, and, as we felt that there might possibly be some systematic velocity difference between stars and interstellar matter, we measured another emission line for this purpose. The $\lambda 3727$ line is by far the strongest emission line in elliptical nebulae, chiefly because it lies in the ultraviolet, where the stellar continuum is weak. The apparently next strongest line in the ordinary photographic region is the $[O III]$ green line $\lambda 5007$, and even this line can be seen only in a very few ellipticals with unusually strong $\lambda 3727$. We therefore selected for an application of this method one of the ellipticals with the strongest known $\lambda 3727$ line, namely, NGC 1052.

Four spectrograms were obtained of this nebula at the prime-focus spectrograph of the 200-inch telescope, two centered in the ultraviolet for measurement of $\lambda 3727$, and two in the green for measurement of $\lambda 5007$. All the spectrograms had a dispersion of approximately 190 Å/mm, and the comparison spectra were provided by helium, neon (ultraviolet region only), and argon (green region only). These plates were measured

independently by Minkowski and by Miss Edith Flather and were reduced to velocities, using for [O II] the nominal wave length λ 3727.00 Å, and for [O III] the value λ 5006.85 Å given by Bowen (1955), with the results presented in Table 1. The final over-all result is that, with respect to the reference system defined by the [O III] green line, the radial velocity of the [O II] line reduced in this way is $+84 \pm 36$ km/sec.

This observed value may be interpreted as follows. The wave lengths of the two components of the λ 3727 blend are 3726.05 and 3728.80 Å (Bowen 1955), and their intensity ratio is (Seaton and Osterbrock 1957)

$$r = \frac{I(3729)}{I(3726)} = \frac{1.569 + 3.825 \times 10^{-4} N_e}{1.056 + 11.1 \times 10^{-4} N_e}, \quad (1)$$

for an assumed electron temperature of 10000° K. If we assume that the measured wave length of the blend is the mean weighted according to the intensity of the individual components, then this mean is

$$\lambda = \langle \lambda \rangle = \frac{3726.05 + 3728.80 r}{1 + r}, \quad (2)$$

and the nominal measured velocity is

$$v = \frac{\lambda - 3727.00}{3727.00} c = \frac{-0.95 + 1.80 r}{1 + r} \frac{c}{3727.00}. \quad (3)$$

TABLE 1
VELOCITY MEASURES OF EMISSION LINES IN NGC 1052

MEASURED PLATE	λ 3727.00			MEASURED PLATE	λ 5006.85		
	R.M.	E.F.	Mean		R.M.	E.F.	Mean
N-599 . .	+1534	+1600	$+1572 \pm 31$	N-618	+1487	+1485	$+1488 \pm 5$
N-633 . .	+1542	+1610		N-661	+1498	+1483	

The velocity calculated according to equations (1) and (3) is plotted as a function of electron density in Figure 1, and it may be seen that the measured result for NGC 1052, $+84$ km/sec, falls completely off the graph, beyond the asymptotic low-density limit. This is doubtless due to the errors inherent in measuring a broad line, but even if we apply the whole probable error, the velocity is $84 - 36 = 48$ km/sec, corresponding to a maximum electron density of about $2 \times 10^2/\text{cm}^3$. The greatest uncertainty in this method of determining the density is in the assumption that the measured wave length is the same as the mean weighted according to intensities, but the margin of error, according to Figure 1, is so great that it is difficult to escape the conclusion that the true intensity ratio is near the low-density asymptotic limit. The assumed electron temperature of 10000° is not critical to the argument, because the upper limit to the density derived from Figure 1 is proportional only to the square root of the temperature. We therefore conclude that the mean electron density in the ionized interstellar matter in the elliptical nebula NGC 1052 is, at most, a few hundred per cubic centimeter.

III. IONIZATION BY ULTRAVIOLET STELLAR RADIATION

In our own Galaxy the ionization of interstellar matter is caused by ultraviolet radiation from main-sequence O and B stars (Strömngren 1939), but elliptical nebulae, since they do not contain such stars (Baade 1951), must have a somewhat different source of

ionization. In those population II systems in which stars have been studied to faint absolute magnitudes, namely, the globular clusters, there are a few hot blue stars with absolute magnitudes fainter than main-sequence stars of the same color (see in particular Arp 1955, who gives separate color-magnitude diagrams for seven clusters). These hot blue stars lie in the color-magnitude diagram both on the "horizontal branch," which curves down to fainter visual magnitudes as the color index becomes more negative, and also above the horizontal branch, off all the sequences that have been named. Now it is somewhat dangerous to conclude on this evidence that the giant ellipticals must also contain the same relative numbers of these kinds of faint blue stars, because it is known from wide-base-line integrated colors (Stebbins and Whitford 1948; Stebbins 1950), from

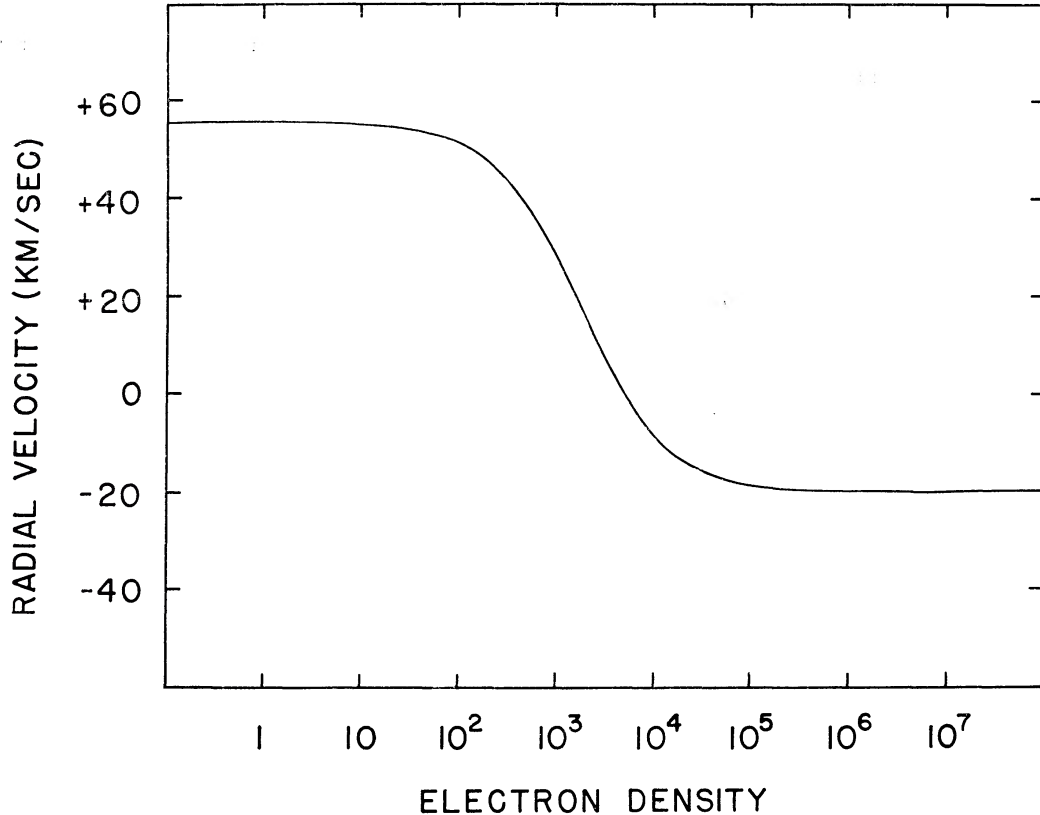


FIG. 1.—Radial velocity for blended [O II] doublet reduced with nominal wave length 3727.00 Å, as a function of electron density, computed for electron temperature 10000°K.

integrated spectra (Morgan 1956; Morgan and Mayall 1957), and from mass-to-light ratios (Schwarzschild 1954) that the stellar contents of globular clusters and of elliptical nebulae are not identical. However, it is fairly well established that both types of systems contain chiefly old stars of roughly comparable ages; and it seems reasonable to suppose that some blue subdwarfs do occur in the ellipticals, though, in the absence of an adequate evolutionary theory of these stars, we can make few definite statements. The only extragalactic population II objects that have been investigated to faint absolute-magnitude limits are the so-called dwarf elliptical nebulae or Sculptor-type systems, which, though fainter absolutely and of lower surface brightness than the giant ellipticals, are nevertheless closely related to them (Baade 1951; Wilson 1955; Holmberg 1957). Some of these dwarf ellipticals have been studied by W. Baade (personal communication, 1958¹) with the 200-inch telescope, and he has found two hot blue stars, one each in two

¹ We are very much indebted to Dr. Baade for permission to use his results in advance of publication.

different systems, that correspond closely to the globular-cluster stars which lie above the horizontal branch. In the Draco system the blue star has a measured color index $B - V = -0.25$ and absolute magnitude $M_v = -2.8$, while in the Leo II system the roughly estimated values are $B - V = -0.25$, $M_v = -2.2$. Though these observations again do not prove that the giant ellipticals contain the same kind of stars, they strengthen the indication that all old stellar systems probably do contain some.

Though we thus consider it likely that giant elliptical nebulae contain some blue stars, we do not have a quantitative idea of just how many there are, and hence we cannot make an accurate calculation of the amount of ionizing radiation to be expected. We have therefore, as an example, calculated instead the amount of ionizing radiation available in a population II object for which the number of blue stars is known, namely, the globular cluster M3. If an elliptical nebula should contain the same relative population of blue stars, with respect to the red giants (which contribute the greatest part of the light) then the M3 calculation would apply directly to it; if the elliptical should contain fewer or more blue stars, then the amount of ionizing radiation would be correspondingly smaller or greater. Though we cannot be certain of the exact population of an elliptical, we can at least have a quantitative idea of the expected ionization in one old system.

The globular cluster M3 has been selected because the data for it are most complete, consisting of both a color-magnitude diagram to the faintest practical limit (Sandage 1953; Johnson and Sandage 1956) and a luminosity function (Sandage 1954, 1957). Our scheme is as follows: First we compute the total amount of ionizing radiation from all the stars in M3, and then the resulting expected strength of the [O II] emission line, assuming that there is sufficient interstellar matter for all the radiation to be absorbed. Then we compute the strength of the continuous spectrum near $\lambda 3727$ resulting from the integrated light of these same stars and from the ratio of line to continuous emission. This ratio is independent of the size of the system and would apply exactly to an elliptical with the same population of stars as M3. Finally, we show by a rough calculation that there probably is enough interstellar gas in a typical elliptical that all the ionizing radiation is absorbed.

The globular-cluster observations give the color indices of the individual stars, while to calculate the amount of ionizing radiation we need to know the effective temperatures and emitting properties of the atmospheres at wave lengths below the Lyman limit at 912 Å. For this purpose we have used the original calculations of Strömgren (1939), which give the ionized volume for stars of each spectral type and absolute magnitude, and which agree reasonably well with observational results (Minkowski 1949). To enter these tables, we need the spectral types of the individual stars, which, since they are not directly observed, must be inferred from the published color indices. For this purpose Table 2 gives the normal (unreddened) colors of main-sequence stars on the Johnson and Morgan (1953) U, B, V photometric system as a function of spectral type, as published by Johnson and Morgan (1953) and by Morgan, Harris, and Johnson (1953). The latter paper does not give the normal $U - B$ colors, which have been derived for the earliest-type stars by us by discussing published observations of little-reddened O stars (Morgan *et al.* 1953; Hiltner and Johnson 1956), using the ratio of color excesses $E_{U-B} = 0.72 E_{B-V}$.

Now the globular-cluster hot blue stars are considerably fainter (absolutely) than the galactic main-sequence stars used in the construction of Table 2, and, as a result, the cluster stars have systematically higher atmospheric pressures than the galactic stars of the same effective temperature. Therefore, the cluster stars do not have the same atmospheric opacity as the galactic stars, and hence they have a different relation between color index and spectral type than the one given in Table 2. The main effect of the higher pressure in these hot stars is that the Balmer lines are all considerably broader and that the effective Balmer limit, where the lines run together, is shifted to-

ward longer wave length, with respect to a star of normal pressure. Calculations of model stellar atmospheres show that wherever the opacity is high, the emergent flux is small; wherever the opacity is low, the flux is large (see, e.g., Underhill 1950), and this result can easily be understood on physical grounds. In our particular case the effect of the longward shift of the effective Balmer limit is to shift radiation in the neighborhood of this limit toward longer wave lengths, so that the flux is somewhat decreased around 3700 Å and somewhat increased around 3800 or 3900 Å. Inspection of the published wave-length response-curves of the U , B , V filters (Johnson and Morgan 1951) shows that the effect is to reduce slightly the flux in the U band and to increase by a greater amount the flux in the B band, so that the $U - B$ index for a cluster star should, for this reason, be more positive, and the $B - V$ index more negative, than for a galactic main-sequence star of the same effective temperature. The resolved Balmer lines shift radiation to both longer and shorter wave lengths and hence have no great effect on the broad-band color indices. Hence the over-all effect of higher pressure is that in a three-color diagram plotted in the usual way (Johnson and Morgan 1953), a star's position is displaced down and to the left with respect to the main-sequence star of the same effective temperature. This discussion follows that of Bonsack, Greenstein, Mathis, Mel-

TABLE 2
NORMAL COLORS FOR GALACTIC MAIN-SEQUENCE STARS

Type	$B - V$	$U - B$	$U - V$	Type	$B - V$	$U - B$	$U - V$
O5	-0.33	-1.15	-1.48	B2	-0.24	-0.86	-1.10
O6	- .33	-1.15	-1.48	B3	- .20	- .71	-0.91
O7	- .32	-1.14	-1.46	B5	- .16	- .56	-0.72
O8	- .31	-1.13	-1.44	B7	- .12	- .47	-0.59
O9	- .31	-1.13	-1.44	B9	- .05	+ .16	-0.21
B0	- .30	-1.11	-1.41	A0	0.00	0.00	0.00
B1	-0.26	-1.00	-1.26				

bourne, Neugebauer, Newburn, Olsen, Tifft, Wahlquist, and Wallerstein (1958), who, however, reached a different conclusion as to the effect of the lines. The result is confirmed by the observed three-color diagrams not only for M3 (Johnson and Sandage 1956) but also for the globular cluster M13 (Arp and Johnson 1955), in both of which the bluest stars do indeed fall below and to the left of the line defined by normal galactic OB stars.

Because of these pressure or luminosity effects, we cannot derive the equivalent spectral types of the globular-cluster stars from their observed colors in a straightforward and unambiguous way. However, according to the discussion above, the V magnitude is least affected by the atmospheric pressure, the B magnitude is most affected, and the U magnitude is only slightly affected. Hence the color index $U - V$ is a better representation of the true temperature than either of the indices $U - B$ or $B - V$ (Greenstein 1958). This reasoning is confirmed by observations of star No. 110 in the catalogue of Arp and Johnson (1955), which has a $B - V$ color of -0.40 , bluer than any galactic star, but a $U - V$ of -1.06 , corresponding, according to Table 2, to an equivalent spectral type of B2, which is roughly consistent with the spectrum of the star, as observed by Münch (Bowen 1956).

We have therefore, for all the bluest stars listed in the photometric catalogue of M3 by Sandage (1953), used the values of $B - V$ and $U - B$ published by Johnson and Sandage (1956) to calculate individual values of $U - V$, which are listed in Table 3. (The brightest star in the table, I-I-57, was a photoelectric standard, so there are both photographic and photoelectric measurements for it, which are listed separately to indi-

cate the observational uncertainties; the other stars were observed photographically only. The faintest star, I-V-37, was not observed by Johnson and Sandage [1956], and the value of $U - V$ listed for it has been extrapolated from a graph relating $U - V$ for the other stars to the color index $C.I.$ given in the catalogue.) This cluster has been considered as completely unreddened by Sandage (1953), Arp (1955), and Johnson and Sandage (1956), but on general grounds it seems more likely to us that it has a slight, but non-vanishing, reddening; hence we have assumed color excesses $E_{B-V} = 0.03$, $E_{U-V} = 0.02$, and therefore have applied a total color excess, $E_{U-V} = 0.05$, to each observed $U - V$ listed in Table 3 to get the normal color of each star. We have then entered Table 2 with this normal color, to obtain the equivalent spectral type for each star, but the two bluest stars, namely, I-II-57 (photographic observation) and I-V-37 (extrapolated color index), have colors bluer than any entry in Table 2 and have been taken to be O5 in type. The discrepancy is no doubt related to the errors of observation and extrapolation, as well as to the fact that even the index $U - V$ contains some

TABLE 3
BLUE STARS AND IONIZED VOLUME FOR M3 POPULATION

STAR	OBSERVED		SPEC.	M_v	$s^3 N^2$	f	$s^3 N^2 / f$
	V	$U - V$					
I-II-57*	14.93	-1.38	O9	-0.8	0.74×10^4	...	...
I-II-57†	15.06	-1.50	O5	-0.6	10.0×10^4	...	...
I-II-57‡	...	...	O8	-0.7	1.48×10^4	1.00	1.48×10^4
I-III-57	16.65	-0.52	B7	+1.0	3.2	1.00	3.2
I-I-58	17.08	-0.82	B3	+1.4	3.4×10	0.83	4.1×10
I-VI-54	17.39	-0.89	B3	+1.7	2.6×10	0.44	5.9×10
I-III-87	17.73	-1.42	O7	+2.0	2.68×10^3	0.26	1.0×10^4
I-V-37	(18.0)	(-1.58)	O5	+2.3	6.95×10^3	0.064	11×10^4

* Photoelectric observation

† Photographic observation.

‡ Spectral type by Popper, adopted type.

luminosity effect. Now the brightest of these blue stars, I-II-57, has been observed for spectral type by Popper (1947), who classified it as an O8 star (it is Barnard 1128 in his Table 3). This type is intermediate between the types derived from the two different color observations of this star, and we have adopted it for our final result, carrying along the other two types in the calculation to indicate the uncertainty.

Now we can use the spectral types to find from Strömgren's (1939) tables the total volume ionized by each star, calculated on the assumption that there is enough interstellar matter to absorb all the emitted ultraviolet radiation. The quantity tabulated by Strömgren is $s N^{2/3}$, which is a function only of spectral type and absolute magnitude, where s is the radius (in parsecs) of the ionized sphere in an assumed homogeneous cloud of density N hydrogen atoms or ions per cubic centimeter. The volume ionized by a single star is thus

$$V = \frac{4\pi (s N^{2/3})^3}{3N^2} \quad (4)$$

and varies inversely with the square of the density, and the total volume ionized by a group of stars is the sum of the volumes ionized by the stars individually. The tables must be corrected for the fact that the absolute magnitudes of the cluster stars are different from the assumed absolute magnitudes used by Strömgren (1939); the correction

is easily made because the ionized volume is directly proportional to the luminosity of the star. The adopted visual absolute magnitudes, based on the distance modulus $V - M_v = 15.7$ (Arp 1955), are listed in Table 3, as well as the derived values of s^3N^2 for each blue star.

Now the catalogue of M3 from which the blue stars listed in Table 3 were selected includes all the stars in a particular area of the cluster down to about apparent magnitude $V = 17.0$, but becomes more and more incomplete for fainter and fainter magnitudes (Sandage 1954). The relative incompleteness has been determined by Sandage (1954) from star counts and is given by him in his Figure 1; the completeness factor, f , which is just the ratio of the number of stars in the catalogue with a given magnitude to the total number in the whole area with the same magnitude, has been read off this figure and is listed in Table 3. Then the total value of s^3N^2 ionized by stars of each kind is given by dividing the value of s^3N^2 for a single star by f , the completeness factor for stars of that magnitude, and the final over-all value of s^3N^2 ionized by all the stars in the area to which the photometric catalogue applies is found by addition of the individual values of s^3N^2/f .

Inspection of the last column of Table 3 shows that, according to it, the bulk of the ionization comes from a number of faint, very hot stars, of which the only observed example is I-V-37. The color index of this star on the $U - V$ system was not directly observed but is the result of extrapolation; it is bluer than any star we know. In addition, the completeness factor is rather uncertain, and, because only one star of this type was observed, the statistical uncertainty is quite large. The bright O star I-II-57 contributes only about 10 per cent of the total ionization according to our adopted spectral type for it, but the range of uncertainty in its color is large enough that, if we had used only the photographically determined color index, as we did for the other stars, we should have approximately doubled the volume ionized by all the stars together. These remarks emphasize the uncertainty of the numerical values; but nevertheless the sum of the entries in the last column in Table 3 is the best available estimate of the total ionization of the globular-cluster blue stars. There is essentially no contribution to the ionization from the more numerous stars still redder than those in Table 3.

The total s^3N^2 , found by summing Table 3, is 13×10^4 , and hence the total ionized volume is $V = 5.4 \times 10^5/N^2$ pc³. This refers only to the volume ionized by the stars within an annulus with radii 100'' and 600'' about the center of the cluster (Sandage 1953); however, as we wish to use results from the luminosity function of Sandage (1954, 1957), which includes all stars within 8' radius of the center, we must finally multiply this volume by the factor 3.5 (Sandage 1954). The final resulting total volume ionized by all the stars within 8' of the center (we shall refer to this sample as the "cluster" in the rest of the paper) is thus $1.9 \times 10^6/N^2$ pc³ or $5.6 \times 10^{61}/N^2$ cm³.

Next we will compute the total emission in the [O II] λ 3727 doublet, by finding the emission coefficient per unit volume and then multiplying by the total ionized volume. For low electron densities (which Sec. II shows are the densities of interest in elliptical nebulae), the emission coefficient is

$$j_{\lambda 3727} = \frac{8.63 \times 10^{-6} \Omega N_e N(O^+)}{\omega T} h\nu \exp \frac{-h\nu}{kT}, \quad (5)$$

where ω is the statistical weight of the lower ⁴S state; N_e and $N(O^+)$ are the electron and singly ionized oxygen densities, respectively; T is the temperature; ν is the frequency corresponding to the wave length λ 3727 Å; and Ω is the collision strength, which has the numerical value 1.28 (Seaton and Osterbrock 1957). If we adopt an estimated electron temperature of 10000° K, the numerical value becomes

$$i_{\lambda 3727} = 3.10 \times 10^{-21} N(O^+) N_e. \quad (6)$$

Now if we assume that half the oxygen is singly ionized (and the other half doubly ionized, because the [O III] lines are also observed) and if we further assume that the abundance of oxygen with respect to hydrogen is $N(\text{O})/N(\text{H}) = 1 \times 10^{-4}$, or one-fifth the observational value for the sun, and if we finally assume that practically all the electrons come from hydrogen, so that $N_e = N(\text{H}) = N$, this becomes

$$j_{\lambda 3727} = 1.55 \times 10^{-25} N^2. \quad (7)$$

All these assumptions are uncertain but appear to us to be the best estimates that can be made at the present time.

The total line emission in $\lambda 3727$ is just the product of the emission coefficient and the total ionized volume and is 8.7×10^{36} ergs/sec, a number independent of the electron density (which must, however, be less than about $10^3/\text{cm}^3$ for the formulae to be valid). This is the amount of $\lambda 3727$ line radiation that would be emitted by the cluster if it contained enough interstellar matter to absorb all the ultraviolet radiation of the hot stars it contains. Of course, the globular cluster M3 does not show the $\lambda 3727$ emission line in its spectrum, nor does any other globular cluster (Mayall 1946), but this can easily be understood because the velocity of escape from a cluster is so low that any ionized interstellar gas would be rapidly lost (Sandage 1957). We are really interested rather in whether, if the cluster population (at least of the brightest stars) were scaled up to the size of an elliptical nebula (which is sufficiently massive to retain interstellar matter), there would be enough gas to absorb the ultraviolet radiation. The answer to this question depends on the way in which the elliptical formed and its subsequent evolutionary history and therefore cannot be completely answered until these are understood. However, as indicated in Section I, there are sound reasons for believing that in typical ellipticals no star formation has occurred for a long time and that all the stars were formed during a relatively brief period. We can thus estimate a lower limit to the amount of interstellar matter in the nebula by assuming that originally all the mass was in the form of stars and that the interstellar matter now in the nebula is matter lost by stars in the course of their evolution. Sandage (1957) has made this calculation, which depends on an assumed luminosity function and an assumed evolutionary history for the brighter stars, and found the total mass lost by the cluster stars to be 1.1×10^3 solar masses. As his assumptions do not conflict with any existing observational data, we have accepted and used this result. On the other hand, the total ionized volume we have derived is $5.6 \times 10^{61}/N^2 \text{ cm}^3$, which by multiplication by the mass density per unit volume, Nm_H , gives the total mass of ionized matter $9.6 \times 10^{37}/N \text{ gm}$ or $4.7 \times 10^4/N$ solar masses. Comparing these two figures, we see that if the mean density of hydrogen atoms or ions is about $0.2/\text{cm}^3$ or larger, the mass of ionized matter is less than the amount of matter returned to interstellar space by stellar evolution alone and that, if there is any concentration of interstellar matter to the center of the nebula by gravitational segregation (Spitzer 1942), there is an even larger available amount of interstellar material. Hence it seems quite likely that if the M3 population were scaled up to an elliptical nebula, it would contain sufficient interstellar matter to absorb all the available ultraviolet radiation.

Now we shall find the total continuous emission at $\lambda 3727$, which is due to the integrated light from the stars in the elliptical nebula or, more precisely, in the scaled-up globular cluster population. We can use the luminosity function to calculate the visual absolute magnitude of the cluster; then, by comparison with the sun, find the energy emitted per unit wave-length interval in the visual region; and, finally, by using the observed energy-curve of a typical elliptical nebula, convert this to the energy emitted in the continuous spectrum near $\lambda 3727$.

The absolute magnitude of the cluster is easily found by summation, using the luminosity function given by Sandage (1957), to be $M_{pv} = -9.0$. Since the sun's absolute

magnitude is $M_{pv} = +4.84$ (Stebbins and Kron 1957), the cluster is brighter than the sun in the visual region by 13.8 mag. or by a factor of 3.3×10^5 . At the representative visual wave length $\lambda 5540$, the mean intensity of the sun is 2.74×10^6 ergs/cm² sec A steradian (Minnaert 1953), which, using the known radius of the sun, can be converted to the statement that the energy emitted by the sun near $\lambda 5540$ is $E_{\odot\lambda 5540} = 5.23 \times 10^{29}$ ergs/sec A. Therefore, the energy emitted by the cluster near $\lambda 5540$ is $E_{\lambda 5540} = 1.7 \times 10^{35}$ ergs/sec A. Although the energy-curve of NGC 1052 has not been directly observed, we may use the results of Tift (1958), who has shown by multicolor photoelectric photometry that all nearby giant ellipticals have nearly the same energy-curve. According to his observations, the mean ratio of energies at $\lambda 3727$ and $\lambda 5540$ is $E_{\lambda 3727}/E_{\lambda 5540} = 0.32$; hence the energy emitted in the continuous spectrum near $\lambda 3727$ is $E_{\lambda 3727} = 5.4 \times 10^{34}$ ergs/sec A, or over a 10-angstrom band the energy emitted is 5.4×10^{35} ergs/sec. Since the total expected $\lambda 3727$ line emission has been computed above to be 8.7×10^{36} ergs/sec, the ratio of line to continuous emission is calculated to be 16, averaged over a 10-angstrom band near $\lambda 3727$. Though we do not have precise spectrophotometry of NGC 1052, the observed ratio of line and continuum intensities is certainly of this order of magnitude. Hence we can conclude that if the population of brighter stars (say brighter than absolute magnitude $M_v = +2$) in M3 were scaled up to the size of a typical elliptical nebula, then the hot blue stars would provide sufficient ionizing radiation, and stellar evolution would have provided sufficient interstellar matter to give emission lines as strong as, if not stronger than, those observed in NGC 1052. This conclusion is not affected by the relative number of main-sequence stars in the nebula and in the cluster, because the visual light comes chiefly from bright yellow giants, the ionizing radiation comes from bright hot blue stars, and the matter returned to interstellar space has come from even brighter stars that have already burned out their interiors. It is only in relatively minor points, such as the exact value of the ratio $E_{\lambda 3727}/E_{\lambda 5540}$, that the number of faint stars makes any difference.

Now NGC 1052 is one of the ellipticals with the strongest known $\lambda 3727$ emission line, the only comparable object being NGC 4278. Among elliptical nebulae in general, there is a continuous range in strength of this line, from these two nebulae down to nebulae in which the line was not observed at all with the equipment used by Humason and Mayall. Since the blue stars will provide enough ionization to explain the entire line strength in NGC 1052, the ellipticals with weaker $\lambda 3727$ could be understood as objects with relatively fewer blue stars. There are wide variations in the number of blue stars from one globular cluster to another (Arp 1955), and it may well be that there are similar variations from one elliptical to another, which could then explain the variations in observed $\lambda 3727$ strength.

IV. IONIZATION BY COLLISIONS

The spectrograms mentioned in Section II show that the $\lambda 3727$ line in elliptical nebulae is invariably broadened, with a width between half-maximum points of the order of 600 km/sec. This result in itself contradicts the expectation that the random velocities of the interstellar matter should be small (Spitzer 1942), an expectation derived from the fast rate of dissipation of energy by a high-temperature gas. The observed line width must be interpreted as resulting from at least partly random supersonic motions of condensations in the interstellar medium or from supersonic turbulence. This turbulence will indeed dissipate energy and thereby provide energy for ionization and line radiation, in addition to that provided by hot blue stars (see Kahn 1955 for a discussion of this effect in H I regions of our own Galaxy). However, the observed line width alone gives almost no information on the details of the turbulence, the way to describe supersonic turbulence is hardly known at all, and the rate of dissipation can be estimated only crudely for strongly supersonic turbulence (Lighthill 1955). We can therefore make only a very rough estimate of the energy available from this

source, based on the order-of-magnitude formula for the dissipation per unit mass per unit time by subsonic turbulence, namely (Heisenberg 1948),

$$\epsilon = \frac{v^3}{l}, \tag{8}$$

where v is a mean velocity of the turbulent elements and l is the size of the system. We take for v a value of 300 km/sec and for l a value of 500 pc, corresponding to the fact that the nucleus in which λ 3727 is observed in NGC 1052 has a diameter of perhaps 5'' and that the distance of this nebula, computed from its red shift with the Hubble constant $H = 75$ km/sec/ 10^6 pc (Sandage 1958), is 19×10^6 pc. With these numbers we find the rate of dissipation to be about 20 ergs/gm sec, while the energy radiated in λ 3727 is $1.55 \times 10^{-25} N_e^2$ (eq. [7]) ergs/cm³ sec or $10^{-1} N_e$ ergs/gm sec. Energy is also emitted in other lines, however, and we may roughly estimate the whole energy emitted by the interstellar gas to be about $5 N_e$ ergs/gm sec (Savodoff 1955). Thus if the mean electron density is 4/cm³, the energy provided by dissipation of supersonic turbulence is just sufficient to balance the energy radiated as line emission, while for lower densities there is more than sufficient energy; for higher densities, not enough. The calculation is too uncertain to give a clear-cut result, but it shows that it is possible that a significant fraction of the energy radiated in the form of light is derived from mass motion.

However, we must then try to understand what is the original source of this energy of mass motion, which is being dissipated by the supersonic turbulence. One possibility is that it comes from the kinetic energy of gas lost from the outer envelopes of stars in late stages of evolution. For if a star is ultimately to become a hydrogen-poor white dwarf and if its mass is originally greater than the Chandrasekhar limit of $1.4 M_\odot$, it must surely, during some stage of its development, lose mass (Chandrasekhar 1939). Now we may picture the stars in an elliptical nebula as moving in highly eccentric orbits about the nucleus, and in the limiting case of a nearly spherical nebula we could imagine the orbits to be nearly straight lines (Belzer, Gamow, and Keller 1951). Though the density of stars is high in the nucleus, it is not so high that the stars actually collide with one another, and the velocities of the stars are so high that there is little gravitational interaction between individual stars. If, however, a star, at any point in its orbit, released a shell of gas with fairly low velocity, then this gas would move in an orbit rather similar to the star's and would also pass through the nucleus. If, however, there were some interstellar gas already in the nucleus, then the new gas falling in would not penetrate it but would instead be stopped by it, because of the relatively short mean free paths of atoms, ions, and electrons (see Spitzer and Baade 1951, who discussed this effect in clusters of galaxies). We may estimate an upper limit to the energy provided in this way by supposing that all the newly liberated gas arrives at the nucleus with a velocity of 500 km/sec and is stopped completely. The energy per unit mass liberated by this source, then, is

$$\begin{aligned} \epsilon &= \frac{1}{M} \frac{dM}{dt} \frac{1}{2} (5 \times 10^7)^2 \text{ ergs/gm sec} \\ &= \frac{1}{M} \frac{dM}{dt} \times 12.5 \times 10^{14} \text{ ergs/gm sec} . \end{aligned} \tag{9}$$

If this is ultimately to provide the whole energy dissipated by line radiation, we must have $\epsilon = 5$ ergs/gm sec, or

$$\frac{1}{M} \frac{dM}{dt} = \frac{1}{\tau} = \frac{1}{2.5 \times 10^{14}} \text{ sec}^{-1} = \frac{1}{10^7} \text{ yr}^{-1}, \tag{10}$$

where τ is roughly the time required for the mass of interstellar matter in the nucleus to increase by a factor e . This process cannot therefore be the main source of energy, be-

cause it would require the rate of accumulation of interstellar matter to be far too rapid. It is likely that actually the turbulent energy is somehow derived from the kinetic energy of the stars, perhaps through gravitational coupling, perhaps through radiative coupling.

V. SUMMARY

The work described here leads to only one clear-cut conclusion, namely, that the density of the ionized interstellar material in one elliptical with very strong emission lines, NGC 1052 (and therefore, probably, also in other ellipticals with weaker lines), is low. The source of ionization energy might be hot blue stars, which would not have to be present in unreasonable numbers at all to provide the observed ionization, but it is also possible that a considerable fraction of the ionization energy could come from the dissipation of turbulent kinetic energy. The mechanism by which turbulence is maintained is not known at all, and it is clear that theoretical investigations of the interaction between fast-moving stars and interstellar gas clouds would be of value in this connection. Further observational studies can also be imagined, such as the absolute strength of the emission lines, the distribution of ionized material through the nebula, the correlation between line strength and line width, etc. (several of these problems are under active investigation by one of us).

The observed mass of interstellar gas is low and could all have resulted from the loss of matter by evolving stars. However, there might have been a much larger supply of gas present from the beginning, as the [O II] line measurements refer only to the ionized phase of the interstellar matter. Observational abundance determinations, now under way, may shed light on this possibility. It would also be profitable to study, with suitable high-resolution radio telescopes, the 21-cm radiation of whatever neutral hydrogen there is in elliptical nebulae. Although 21-cm emission has been reported for the dwarf elliptical M32 (Heeschen 1957), this report has not been confirmed by other observers (Raimond and Volders 1957), and there are no published data for any typical giant elliptical.

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