PHYSICAL CONDITIONS IN THE NUCLEUS OF THE SEYFERT GALAXY NGC 1068

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ABSTRACT

Photographic spectrophotometric measurements have been made of the emission lines of the nucleus of the Seyfert galaxy NGC 1068 in order to identify the mechanism by which excitation and ionization energy is supplied to the gas. The absolute calibration was provided by measurements with the same equipment of standard planetary nebulae with known fluxes. The observational result is thus a table of relative line strengths (in energy units) over the wavelength interval λλ 3346–7330. In addition the total flux (in energy units) in the strong [O III] λ 5007 line was measured photoelectrically, as well as the continuum flux in the near ultraviolet.

The Balmer gradient is steeper than expected for either a pure recombination spectrum or a thermal-collisional spectrum with $T \geq 8000°$ K. The electron temperatures indicated by [O III] and [N II] lines show that the ionization is not due to collisions of thermal electrons. The strength of [O I] and [N I], and also the absence of the Bowen fluorescent lines of O III indicate there is a substantial amount of neutral gas mixed in with the ionized gas and, therefore, that the ionization mechanism is not completely ultraviolet light. Thus a considerable part of the ionization is probably due to fast protons. The fastest protons would have to have energy about 25 MeV for their ranges to be large enough to excite the entire nucleus if they come from a single source, but the high-ionization lines (such as [Fe X]) that would be expected to result from such fast protons are not observed The observed velocities of the gas correspond to energies ranging up to 25 KeV for protons, sufficient to produce [Ne V] and [Fe VII] which are in fact observed. Thus it is likely that frequent collisions between high-velocity clouds produce a large part of the observed ionization.

The observed synchrotron spectrum, extrapolated to the ultraviolet, does not contain sufficient high-energy photons to explain the observed ionization. If the proton energy spectrum is sufficiently steep to low energies, the collisions tend to populate the $2s$ and $2p$ states of neutral hydrogen by resonance collisions, which in turn leads to self-absorption of the Balmer emission lines and strong emission of Lyman α and the 2-photon continuum by the nucleus.

INTRODUCTION

Seyfert galaxies are distinguished from "normal" galaxies by broad, strong emission lines superimposed on a continuous spectrum with stellar absorption lines (Seyfert 1943). On direct photographs these galaxies appear as typical spirals, except that they usually have especially small, bright nuclei (Seyfert 1943; Morgan 1958; Sandage 1961). Although many of the Seyfert galaxies are weak radio sources (Heeschen and Wade 1964), at least one, NGC 4151, is not, being at least ten times fainter than NGC 1068 in the radio frequency region even though the brightness in the optical region of the two galaxies is comparable.

The Seyfert galaxies are interesting in themselves, but they are also worthy of study because of the possible similarities between them and the quasi-stellar radio sources (Burbidge, Burbidge, and Sandage 1963). Like the Seyfert galaxies, the quasi-stellar radio sources have broad emission lines covering a wide range of ionization, up to [Ne V] (Greenstein and Schmidt 1964), and therefore the nuclei of Seyfert galaxies may perhaps be thought of as miniature quasi-stellar radio sources located at the centers of otherwise normal galaxies.

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We have therefore tried to study the physical conditions in the typical Seyfert galaxy NGC 1068, with special attention to the ionization mechanism by which the ionization energy and the thermal energy radiated in the emission-line spectrum is supplied to the gas. The main observational part of our program consists in spectrophotometric measurements of the relative intensities of the emission lines in this galaxy. Such measurements were originally made by Seyfert (1943), but as these were made many years ago and have been questioned by theoreticians interested in the interpretation of Seyfert galaxies (Woltjer 1959), we have thought it important to repeat them, covering a slightly more extended wavelength interval. In addition we have made an absolute measurement of the total flux from the nucleus of NGC 1068 in the [O III] λ 5007 emission line, and this measurement coupled with the relative intensity measurements gives the absolute intensity in all the observed emission lines. Finally, we have measured the absolute flux in the ultraviolet continuum to check the possible excitation mechanisms.

SPECTROPHOTOMETRY

All of the relative intensity measurements were made photographically using the 82-inch telescope at the McDonald Observatory. Four sets of spectra were taken, two sets with the Cassegrain spectrograph, using quartz prisms to cover the ultraviolet and blue spectral regions, and glass prisms to cover the photographic and visual regions to Hα; and two sets with the prime-focus spectrograph, using the same grating to cover both the visual spectral regions to Hα, and the near infrared from Hα to longer wavelengths. The dispersions range from 200 to 400 Å/mm approximately, and all the spectrograms were widened by trailing the nucleus of NGC 1068 on the slit. A range of exposures was taken so that all lines from the strongest to the weakest which were observable above the integrated continuum of the galaxy could be measured. The calibration was provided by spot-sensitometer exposures on film taken from the same box as the stellar spectrograms and processed along with them. The wavelength sensitivity of the system was found by making measurements with the same equipment of standard planetary nebulae, chiefly NGC 7027 and NGC 7662, in which the absolute intensities of the emission lines have previously been measured by Liller and Aller (1963) and by O'Dell (1963).

The final results, covering the wavelength range from λ 3312 to λ 7330, are listed in Table 1, which gives, in addition to the measured line strengths, upper limits to the strengths of some of the unobserved but physically important lines. The precision of the measurements is difficult to specify accurately, but from the internal consistency (most lines were measured three or four times on different spectrograms, though some of the weaker lines were measured only once) we estimate the limits of error to be about ±30 per cent, to which whatever error is present in our determination of the wavelength sensitivity should be added.

The Hγ and [O III] λ 4363 lines are not completely resolved, because of the large intrinsic line widths, but they are nearly resolved and their individual intensities are fairly well determined. The Hα and [N II] λλ 6548, 6583 lines are more intimately blended, as shown in the profile of Figure 1, but by using the known wavelengths and also the known relative intensities of the two [N II] lines, it is possible to determine each intensity with somewhat less accuracy.

Over the spectral range λλ 3727–6730 covered by Seyfert (1943), his measurements and ours do not differ appreciably except that, according to our measurements, Hα and the red [N II] lines are approximately twice as strong as indicated by his measurements. We have found no new lines in the spectral region measured by Seyfert, but we have added the ultraviolet [Ne V] lines, first observed in NGC 1068 by Roberts (1963), and the near-infrared [Ar III] and [O II] lines. We have also listed in Table 1 for comparison the relative intensities of the same lines as measured in NGC 7027 (Aller, Bowen, and Minkowski 1955; Liller and Aller 1963; O'Dell 1963), and also the intensities in NGC 7027 corrected for interstellar reddening (O'Dell 1963). This planetary nebula, which has a relatively atypical spectrum with respect to the other planetary nebulae, has a spectrum somewhat similar in relative intensities to the Seyfert galaxies.

ABSOLUTE FLUXES

The absolute measurement in energy units of the emission-line flux from NGC 1068 was made photoelectrically, using the Cassegrain scanning spectrograph on the 100-inch telescope at Mount Wilson. All the photoelectric measurements were made with an entrance slit 10″ × 20″, considerably larger than the nucleus, but we believe that the central concentration is sufficiently great so that at least half of the light measured actually was emitted in the nucleus. An exit slit with the resolution of 30 Å was used, centered on the redshifted λ 5007 line, and the flux was measured relative to the continuum of Vega through the use of the standard star HD 15318. With this apparatus the flux from NGC 1068 in λ 5007 was observed to be 2.0×10^{-11} erg/cm^2 sec, using the calibration of HD 15318 in energy units due to Code (1960) and Oke (1964*a*). This meas-

TABLE 1

RELATIVE STRENGTHS (IN ENERGY UNITS) OF EMISSION LINES IN THE NUCLEUS OF NGC 1068

Wavelength (λ)	Ion	Relative Strengths: Observed (NGC 1068)	For Comparison: Observed (NGC 7027)	For Comparison: Corrected (NGC 7027)
3312	O III	< 0.3	0 8	2 1
3346	[Ne V]	1 9	1 6	4 2
3425	[Ne V]	6 8	5 0	13
3444	O III	< 0 4	2 5	6 3
3726+3729	[O II]	9 3	1 4	3 5
3868	[Ne III]	7 8	5 0	12
4068+4076	[S II]	1 2	0 7	1 6
4101	Hδ	0 7	1 4	2 6
4340	Hγ	3 0	3 2	4 7
4363	[O III]	1 3	1 8	2 6
4686	He II	3 4	4 2	4 6
4711	[Ar IV]	< 0 6	0 7	0 8
4740	[Ar IV]	1.2	0 9	1 0
4861	Hβ	10	10	10
4959	[O III]	56	51	48
5007	[O III]	158	158	146
5199	[N I]	2 9	0 2	0 2
5755	[N II]	< 0 7	1 4	0 8
5876	He I	1 0	2 1	1 1
6087	[Fe VII]	1 4	0 2	0 1
6300	[O I]	5 9	5 0	2 0
6364	[O I]	1 7	1 5	0 6
6374	[Fe X]	< 1 5	...	...
6548	[N II]	24	8	3
6563	Hα	125	83	29
6583	[N II]	70	26	9
6717+6730	[S II]	21	1 9	0 6
7136	[Ar III]	4 0	8 5	2 2
7320+7330	[O II]	3 5	13	3 1

urement, together with Table 1, may then be used to find the absolute flux in any observed emission line from NGC 1068.

The absolute flux in the continuum of the nuclear region of NGC 1068 was also measured with the scanner in the same way, to check the observational result of Walker (private communication) that it is abnormally bright in the near ultraviolet. Our results, derived from the same absolute calibration mentioned above, are listed in Table 2.

TEMPERATURE AND DENSITY

We next turn our attention to the interpretation of these measurements to find the physical conditions in the nucleus of NGC 1068. We shall tentatively assume that there is not sufficient interstellar absorption within the nucleus to appreciably modify the relative intensities, and since NGC 1068 is at high galactic latitude the interstellar reddening in our own Galaxy is probably quite small; so we may consider the observed relative intensities to be the same as the average relative intensities in the nucleus. The wide range of ionization in the observed spectrum immediately shows that there is a wide range of physical conditions in the nucleus, and the values we derive for the density, temperature, etc., must be regarded as averages only.

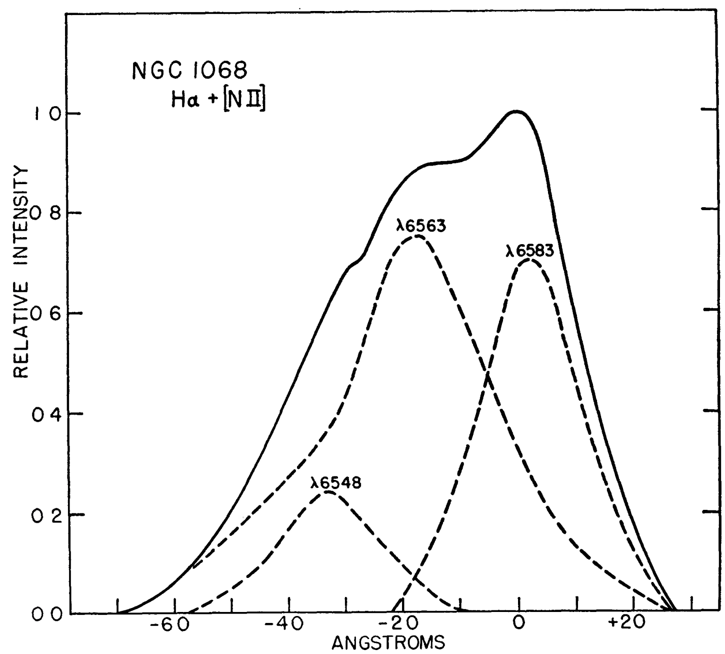

FIG. 1.—Observed profile of [N II] λλ 6548, 6583 and Hα λ 6563 in NGC 1068, and reconstruction of three separate line profiles.

TABLE 2

ABSOLUTE FLUXES IN CONTINUUM FROM CENTRAL REGION OF NGC 1068

λ (Å)	F_ν (erg/cm² sec c/s)
3300	$3\ 0\times10^{-25}$
3390	$3\ 0\times10^{-25}$
3500	$2\ 8\times10^{-25}$
3600	3.1×10^{-25}
3800	$3\ 5\times10^{-25}$
4250	$6\ 0\times10^{-25}$

First of all, the ratios of strengths of the [O III] lines λλ 5007, 4959, and 4363 may be used to find the electron temperature, T, and using the numerical values of Seaton (1960) the result is $T = 10200°$ K. Likewise the ratios of the strengths of the [N II] lines λλ 6583, 6548, and (unobserved) 5755 give $T < 8200°$. The difference between these two temperatures may be real, indicating differences in the regions where the [O III] and the [N II] lines are emitted, or it may merely reflect minor uncertainties in the calculated collision strengths used in deriving them.

These temperature determinations immediately show that the ionization mechanism in the nucleus of NGC 1068 cannot be collisional ionization by thermal electrons, for the calculations of Parker (1964) and House (1964) show that with this mechanism a temperature of at least $T = 30000°$ is required for there to be any appreciable amount of O^{++}, and a temperature of at least 15000° is required for the existence of N^{+}. The quoted calculations were made under the assumption that two-body radiative recombination is the only recombination process, but more recently Burgess (1964; see also Burgess and Seaton 1964) has shown that actually at high temperatures dielectronic recombination is more effective. We have therefore made an approximate calculation of the collisional ionization of several important elements taking into account this process. Since the necessary dielectronic recombination cross-sections are not available except for He^{+} and Fe^{+13} (Burgess 1964), we have been forced to estimate them approximately using Burgess' calculations as a guide. The formulae for the two-body recombination coefficients and collisional ionization coefficients recommended by Seaton (1962a) were adopted, and the correction factor f to be applied to the radiative recombination coefficient to obtain the total recombination coefficient (including the effects of dielectronic recombination) was approximated by the expressions

$$\begin{aligned} f &= \tfrac{100}{3} && \text{if } \frac{\chi}{kT} < 1 , \\ f &= \tfrac{100}{3} - \tfrac{97}{12}\left(\frac{\chi}{kT} - 1\right) && \text{if } 1 \leq \frac{\chi}{kT} \leq 5 , \\ f &= 1 && \text{if } 5 < \frac{\chi}{kT} , \end{aligned} \tag{1}$$

where χ is the excitation potential of the lowest excited level that is connected by an allowed dipole transition with the ground level (of the ion that recombines).

The equation of collisional ionization equilibrium then becomes

$$\frac{N[X^{+(m+1)}]}{N[X^{+(m)}]} = \frac{10^{(3\,0-5040 I_m/T)} \zeta T}{f(m+1)^2 I_m{}^2} , \tag{2}$$

the same as used by Seaton (1962a) except for the dielectronic recombination correction. Here ζ stands for the number of electrons in the outermost shell, each with ionization potential I_m, where m is the number of electrons already lost by the ion X^{+m}. Calculations of the collisional ionization were made according to equation (2) for a number of elements, and the results for oxygen are exhibited in Figure 2. Comparison of this figure with House's (1964) Figure 2 shows the expected result that the degree of ionization is unchanged by the effects of dielectronic recombination at low temperatures, but that at high temperatures the ionization is lower at a given temperature. Figure 2 shows that there is essentially no collisionally ionized O^{++} at 10000°, and the mechanism of ionization in NGC 1068 cannot be thermal collisional ionization. Calculations for other elements furthermore show that according to equation (2) temperatures T greater than or equal to 150000° are required for there to be any appreciable amount of Ne^{+4} and Fe^{+6}, both of which are observed in NGC 1068. If this high temperature actually existed several other lines of higher excitation, particularly of Fe VII, would undoubtedly be observed in NGC 1068, and their absence is further confirmation that another mechanism than thermal electron collisions is responsible for the observed ionization.

Some information concerning the electron density in the nucleus of NGC 1068 can be obtained from the relative intensities of the lines of [O II], [S II], and [Ar IV]. First, for [O II] the relative intensities of the ultraviolet and infrared lines are given in the low-density limit by the expression

$$\frac{I(\lambda 3726+\lambda 3729)}{I(\lambda 7320+\lambda 7330)}=5.5\,e^{12600/T} \tag{3}$$

(Seaton 1960). The observed intensities do not satisfy this equation for any positive temperature; the intensities of λ 3726 and λ 3729 are much less than those predicted

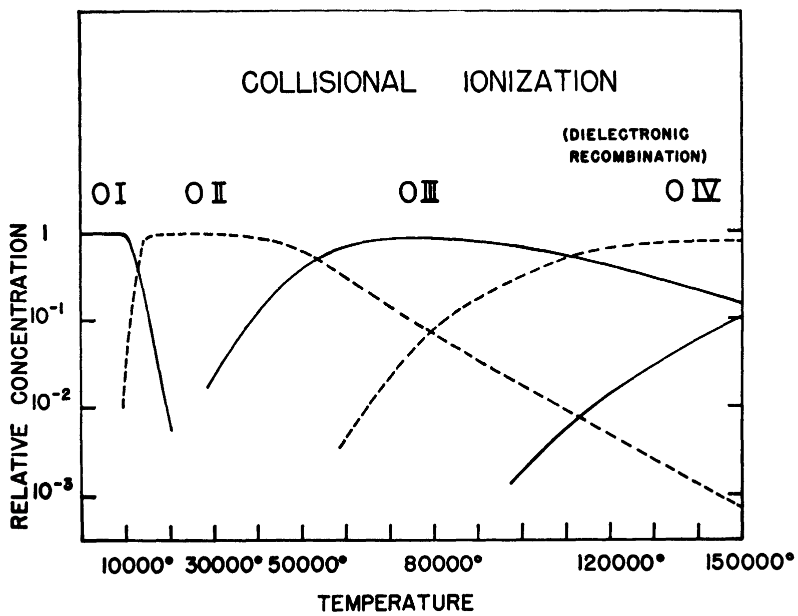

FIG. 2.—Thermal collisional ionization of O taking account of dielectronic recombination

by this equation for any reasonable temperature. This result indicates that the ^2D upper level of O^+ is collisionally de-excited (Seaton and Osterbrock 1957), which implies that

$$N_e q(^2D, {}^4S) > A(^2D, {}^4S)\,, \tag{4}$$

where $N_e q(^2D, {}^4S)$ is the collisional de-excitation rate, and $A(^2D, {}^4S)$ is the radiative de-excitation rate. The collisional de-excitation rate may be written

$$q(^2D, {}^4S)=\frac{8.63\times 10^{-6}\Omega(^4S, {}^2D)}{g(^2D)T^{1/2}}, \tag{5}$$

where $\Omega(^4S, {}^2D)$ is the collision strength (Seaton 1958), and $g(^2D)$ is the statistical weight of the upper level. Using the collision strengths listed by Seaton (1958) and the transition probabilities given by Seaton and Osterbrock (1957) the result is, for an assumed $T = 10000°$, $N_e > 4 \times 10^3$ per cm^3 in the region where the [O II] lines are emitted.

Likewise, for the [S II] lines we find, using the transition probabilities calculated by

Garstang (1952), and Naqvi and Talwar (1957) and the collision strengths listed by Seaton (1958), in the low-density limit

$$\frac{I(\lambda 6717+\lambda 6730)}{I(\lambda 4068+\lambda 4076)}=12.9\,e^{14000/T}. \tag{6}$$

The observed ratio in NGC 1068 corresponds to $T = 52000°$, but it is impossible that this temperature be real, because according to the ionization calculations described above, sulfur would be much more highly ionized than S^+ due to thermal electron collisions alone at this temperature. The result thus is that there is some collisional de-excitation of the upper ^2D state of S^+, from which the λ 6717 and λ 6730 lines arise, but not as much as in the case of O^+. By an equation similar to equation (4), using the [S II] transition probabilities and collision strengths, we find in the region where the [S II] lines are emitted, $N_e \gtrsim 4 \times 10^4$ per cm^3. The atomic parameters for S^+ are less accurately calculated than for O^+, and the numerical result for the electron density is correspondingly less certain (Seaton 1960).

Finally, for [Ar IV] the line λ 4740 is definitely observed in NGC 1068, while λ 4711 is absent, the lower limit to the ratio of strengths of these lines being approximately 2. At low densities the predicted ratio of strengths of these two lines is $\frac{2}{3}$ (Seaton 1958), and we may therefore conclude that the $^2D_{5/2}$ level from which λ 4711 arises is appreciably collisionally de-excited. Again we may use an equation similar to equation (4), now applied to the $^2D_{5/2}$ level of Ar^{+3}. The transition probability is $A(^2D_{5/2}, {}^4S_{3/2}) = 0.0026$ sec^{-1} (Naqvi and Talwar 1957), while the collision strength may be estimated from Seaton's calculation for the isoelectronic ion S^+ together with the variation with degree of ionization (Seaton 1964) to be approximately $\Omega(^4S, {}^2D) = 1.0$. We therefore determine the electron density in the [Ar IV] emitting region to be $N_e \approx 2 \times 10^5$ per cm^3. This result is the least certain of all, because of the estimates involved, but all three determinations agree in assigning a relatively high electron density, similar to that in the denser planetary nebulae.

Next we may obtain further information on the density from the observed total luminosity of the nucleus in the hydrogen emission lines. The measured absolute flux in λ 5007 given above, together with the relative intensities in Table 1, show that the observed flux in Hα from the central region of NGC 1068 is 1.6×10^{-11} erg/cm²/sec. The measured redshift of the galaxy is +1070 km/sec (Humason, Mayall, and Sandage 1956), corresponding with an adopted Hubble constant of 100 km/sec/mpc (Sandage 1963) to a distance of 1.1×10^7 pc. The total luminosity of the center of the galaxy in Hα is thus $L(H\alpha)$ 2.3×10^{41} erg/sec. Suppose we first consider the nucleus as a sphere with constant density and radius r, so that the luminosity in Hα is given by the expression

$$L(H\alpha)=\frac{4\pi r^3}{3}\,j\alpha. \tag{7}$$

According to Woltjer (1959) the radius of the nucleus of NGC 1068 is 1″, corresponding at the assumed distance of 50 pc. The emission coefficient per unit volume is given by

$$j_\alpha = N_e N_p\, \alpha_{32} h\nu_\alpha, \tag{8}$$

where α_{32} is the effective recombination coefficient for the production of Hα (Seaton 1960). The observed Balmer decrement in NGC 1068 does not agree with any accurately known physical theory, but for reasons to be made clear below we believe it to result from recapture followed by strong self-absorption of the lower Balmer lines by H atoms in the $2s$ and $2p$ states. Under this assumption all recaptures to levels greater than or equal to 3 are effective in producing Hα, and for an assumed temperature $T = 10000°$, $\alpha_{32} = 1.76 \times 10^{-13}$ cm^3 sec^{-1} (Spitzer 1951; Seaton 1960). Thus, substituting in equations (7) and (8) above, under the assumption $N_e = N_p$, we find $N_e = 1.6 \times 10^2$ per cm^3. This density, together with the radius given above, leads to a mass $2 \times 10^6 M_\odot$ of ionized gas in the nucleus.

It should be remembered that there is some ambiguity here because the measurement of emission-line intensity was made through a $10'' \times 20''$ diaphragm, while the nucleus is considerably smaller. If our value for the intensity from the nucleus is too large, then of course these results will also be too large by the same factor.

The fact that the density found in this way from the observed Hα flux is so much smaller than the density found from the forbidden-line ratios means that the entire volume assumed for the nucleus cannot be filled with ionized gas, but rather that a smaller volume is filled by gas of higher density, of the order of $N_e = 10^4$ per cm^3. Thus it is likely that there are strong density fluctuations within the nucleus which might be idealized by describing it as consisting of clouds of ionized material occupying 10^{-3} of the total volume of the nucleus, separated by either vacuum or by neutral material and on this picture the mass of ionized gas is about $3 \times 10^4 M_\odot$. This is, no doubt, an extreme oversimplification, but it is certain that there are regions covering a wide range in electron density within the nucleus.

The helium lines probably arise almost entirely from recombination, and from the observed relative strengths of λ 4686 and λ 5876 we find $N(He^+)/N(He^{++}) = 2.5$, using the recombination coefficients listed by Seaton (1960). Likewise, if we adopt the view that the Hβ strength is correctly predicted by the recombination theory, then $N(He^+) + N(He^{++})/N(H^+) = 0.14$, a fairly typical abundance ratio.

IONIZATION

The observed emission lines in NGC 1068, ranging from [O I] to [Ne V] and [Fe VII], show that a wide range of ionization is present, up to an ionization potential of approximately 100 eV. On the other hand, the absence of [Fe X] λ 6374 shows that there is not any appreciable amount of Fe^{+9}, that is, that ions with ionization potential as high as 235 eV are not appreciably ionized. This conclusion is somewhat dependent on the cross-sections for collisional-excitation of [Fe VII] λ 6087 and [Fe X] λ 6374, both of which are unknown. From the work of Blaha (1962) and Seaton (1964) it appears likely that both ions are collisionally excited primarily as permitted electric-quadrupole transitions. In the case of Fe VII the excitation probably occurs mainly from the ground ^3F term to the second excited ^3P term, followed in approximately one-third of the excitation processes by cascading to the ^1D second excited term from which the emission of λ 6087 occurs (Pasternack 1940; Garstang 1964). The higher degree of ionization of Fe^{+9} tends to make its collisional excitation cross-section smaller, so that finally the λ 6087 and λ 6374 cross-sections are of the same order of magnitude. Calculated collisional-excitation cross-sections are available for [Ne III] and [Ne V] lines (Seaton 1958), and the observed strengths listed in Table 1 show that the amounts of these two ions in NGC 1068 are comparable. The relative amount of O^+ is less certain because of the large correction for collisional de-excitation discussed above, but nevertheless it is fairly certain that $N(O^+)/N(O^{++}) < 1$.

The absence of the O III permitted lines $\lambda\lambda$ 3312 and 3444, which are excited in normal planetary nebulae by the Bowen (1935) resonance-fluorescence process, is a striking peculiarity of the emission-line spectrum of NGC 1068. These lines are observed in all planetary nebulae in which He II and [O III] lines occur, and are known to result from an accidental coincidence between the He II Lα line and the O III $2p^{2\,3}P_2$–$2p3d\ ^3P_2$ line (Bowen 1935). The only explanation that can be given for the absence of these resonance-fluorescence lines in NGC 1068 is that the He II Lα photons must be destroyed before they are converted into observable O III line photons. The most likely absorption process for these photons is photoionization of H^0 or He^0, and the absence of the Bowen resonance-fluorescence lines of O III thus indicates that neutral hydrogen (or helium) is intimately mixed with ionized He^+ and O^{++}. This situation could not occur if the ionization were due to ultraviolet radiation from a single source, because of the well-known sharp boundary between the inner ionized zone and the outer neutral zone (Strömgren 1939). We can thus eliminate one conceivable source of ionization.

Another possible mechanism of ionization which might be considered for NGC 1068 is collisional ionization by fast particles. If an electrically neutral mixture of protons and electrons is accelerated to a high velocity, then protons acquire much the greater energy, and we therefore discuss briefly the ionization by fast protons. There are previous discussions of this problem in the context of the nuclei of normal galaxies (Burbidge, Gould, and Pottasch 1963) and of Herbig-Haro nebulosities (Davidson 1964). Unfortunately, only a few accurately measured or calculated collisional ionization cross sections (Fite 1962; Bates 1962) are available, and our discussion cannot have high accuracy. We shall be guided by the result that in the first Born approximation, $Q(Z, E)$, the cross-section for ionization of a hydrogen-like ion with nuclear charge Z by a proton with energy E is related to $Q(1, E/Z^2)$ the cross-section for ionization of H by a proton with energy E/Z^2 by

$$Q(Z, E) = Z^{-4}Q(1, E/Z^2) \tag{9}$$

(Bates 1962). This suggests that in the more complicated case of a non-hydrogen-like ion with ξ_m electrons in its outer shell, each with ionization potential L_m, the ionization cross-section $Q(\xi_m, L_m, E)$ is given in terms of the hydrogen ionization cross-section $Q(1, I_H, EI_H/I_m) = Q(1, EI_H/I_m)$ by the expression

$$Q(\xi_m, I_m, E) = \xi_m \left(\frac{I_H}{I_m}\right)^2 Q(1, EI_H/I_m). \tag{10}$$

Therefore if $F(E)dE$ is the flux of protons in the energy range E, dE, then the ionization rate of ions of type X^{+m} with ionization potential I_m is $N(X^{+m})q_m$, where

$$q_m = \int_0^\infty F(E)Q(\xi_m, I_m, E)\,dE = \xi_m \left(\frac{I_H}{I_m}\right)^2 \int_0^\infty F(E)Q(1, EI_H/I_m)\,dE. \tag{11}$$

In particular if the flux of protons can be represented by a power-law spectrum,

$$F(E) = KE^{-\gamma} \tag{12}$$

down to energies so low that the cross-section has dropped almost to zero (approximately 5 keV for H [Fite 1962] and correspondingly higher for other elements of higher ionization potential) then

$$q_m = C\xi_m \left(\frac{I_m}{I_H}\right)^{-(\gamma+1)}, \tag{13}$$

where

$$C = K\int_0^\infty y^{-\gamma} Q(1, y)\,dy \tag{14}$$

has the physical meaning of the collisional ionization rate of neutral H per atom per unit time. The collisional ionization rate is balanced by the recombination rate $N(X^{+m+1})$-$N_e \alpha_m$, where

$$\alpha_m = 2.1 \times 10^{-11}(m+1)^2 T^{-1/2} \tag{15}$$

is a sufficiently accurate approximation for the recombination coefficient (Seaton 1962*a*). We have omitted the correction for the dielectronic recombination rate because it appears likely that T is of the order of or less than 20000°, and therefore that $\chi/kT > 5$

for all ions of interest. The collisional ionization equilibrium equation therefore becomes

$$\frac{N(X^{+m+1})}{N(X^{+m})}=\frac{D\xi_m}{(m+1)^2}\left(\frac{I_H}{I_m}\right)^{\gamma+1}, \tag{16}$$

where

$$D=\frac{K\int_0^\infty y^{-\gamma}Q(1,\, y)\,dy}{2.1\times 10^{-11}N_eT^{-1/2}} \tag{17}$$

is the number of collisional ionizations of H^0 per neutral atom per unit time divided by the number of recombinations of H^+ per ion per unit time. Notice that the ionization

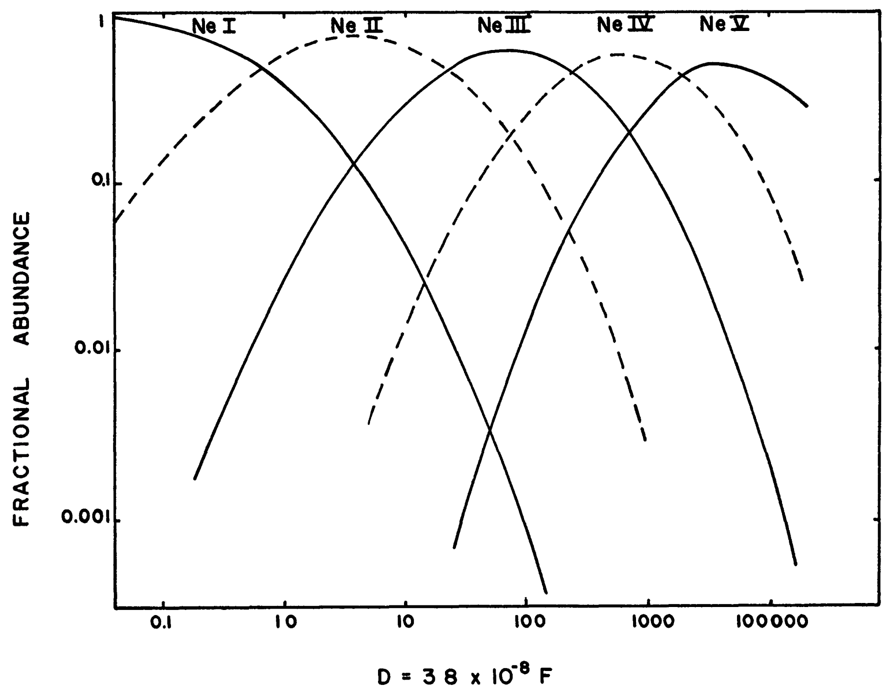

FIG 3.—Collisional ionization of neon as a function of fast proton flux, for $\gamma = -2$ spectrum of proton energies, with $N_e = 10^4$ cm^{-3}, $T = 10^4$, $D = 3\ 8 \times 10^{-8}\,F$, F = flux of protons with $E > 5$ keV.

potential occurs to the power $\gamma + 1$ in equation (16), is contrast to the exponential dependence of the Saha equation, and that the cross-section occurs only as a definite integral in equation (17).

We have made calculations of the ionization equilibrium according to equation (16) for a number of elements of interest in the Seyfert galaxies, using $\gamma = 2$ purely for illustrative purposes, and the result for one element, neon, is shown in Figure 3. To evaluate the definite integral, we have used the measurements of the hydrogen ionization cross-section by Fite, Stebbings, Hummer, and Brackmann (1960). If the flux of protons with energy greater than 5 keV is written F, then with the nominal values $N_e = 10^4$ per cm^3 and $T = 10000°$, we obtain $D = 3.8 \times 10^{-8}\,F$. It can be seen from Figure 3 that at a given F, N_e, and T only a limited number of ions of any particular element can exist, and that the degree of ionization is a function of F. Thus if the ionization mechanism in NGC 1068 is due to high-energy proton collisions, different values of F must exist in various regions of the nucleus. The observed [Ne v] lines show that in some regions F

must be as high as 10^{10} protons/cm^2 sec with energies $E > 5$ keV, that is, approximately 10^2 protons per cm^3 with velocities greater than 800 km/sec.

Another possible schematic form that could be assumed for the proton spectrum is

$$F(E) = \begin{cases} \dfrac{F_0}{E_0} & 0 \leq E < E_0 \\ 0 & E_0 < E \,, \end{cases} \tag{18}$$

that is, a flat spectrum up to a maximum energy E_0 and no protons with higher energy. We have not repeated the calculations of the ionization equilibrium for this form of the spectrum because a qualitative discussion is sufficient. Theory (Bates 1962) and observation (Fite *et al.* 1960; Fite 1962) show that the ionization cross-section is small for protons with energies below a threshold $E < E_t$, becomes large at higher energies, and then slowly decreases at very high energies. According to our assumption of equation (10), the threshold energy E_t is proportional to the ionization potential I_m and the experimental data give for $H^0(I_m = 13.6$ eV), $E_t = 5$ keV approximately (Fite *et al.* 1960), while for $Ne^0(I_m = 21.5$ eV), $E_t = 4$ keV approximately (Gilbody and Hasted 1957). Therefore, if we adopt the flat spectrum of equation (18), we see qualitatively that all ions with $E_t \leq E_0$ will be present, while ions with $E_t \geq E_0$ will not occur. The observations of NGC 1068 show that ionization can occur up to potentials of about 100 eV, corresponding approximately to $E_0 > E_t \approx$ 20–30 keV, while $E_0 < 50$ keV or so from the absence of [Fe x] lines. Now the observed widths of the emission lines in NGC 1068 range from 2400 km/sec to 3600 km/sec (Seyfert 1943), and since a proton with velocity 2000 km/sec has an energy of 20 keV, it is clear that particles with about the right velocities to cause the observed ionization do exist in the nucleus of this Seyfert galaxy.

Up to this point we have been considering the fast particles responsible for the ionization as protons. In fact, however, protons passing through a gas can capture electrons from the gas by charge exchange, thus becoming fast hydrogen atoms and, in turn, these fast hydrogen atoms can lose electrons either by ionization or by charge exchange, thus becoming high-energy protons again. Suppose we consider, for simplicity, high-energy protons and hydrogen atoms passing through a medium consisting of protons, electrons, and hydrogen atoms present in the amounts N_p, N_e, and N_H per unit volume, respectively. If we write f^+ and $f_0 = 1 - f^+$ as the relative amounts of protons and hydrogen atoms in the high-energy beam, then the equation of charge equilibrium among the high-energy particles is

$$f^0[\sigma_i(H^+)N_p + \sigma_i(H)N_H + \sigma_i(e)N_e] = f^+[\sigma_c(H)N_H + \sigma_c(e)N_e] \,, \tag{19}$$

where $\sigma_i(H^+)$ is the cross-section for ionization of a fast hydrogen atom by a proton (Bates and Griffing 1953), $\sigma_i(H)$ is the cross-section for ionization of a fast hydrogen atom by a hydrogen atom (Bates and Griffing 1955), and $\sigma_i(e)$ is the cross-section for ionization of a fast hydrogen atom by an electron (Fite 1962), $\sigma_c(H)$ is the cross-section for capture of an electron by a fast proton from a neutral hydrogen atom (Bates and Dalgarno 1953), and $\sigma_c(e)$ is the cross-section for capture by a fast proton of a free electron. All these cross-sections, which are of course energy-dependent, are tabulated in the references cited, except for the last, which was calculated according to the formulae given by Bethe and Salpeter (1957). The charge equilibrium for high-energy particles in a completely neutral hydrogen gas ($N_p = N_e = 0$) have been solved by Bates and Griffing (1955) and are shown in Figure 4, and we have obtained the solution for the case perhaps more relevant to NGC 1068 of a half-ionized gas ($N_H = N_p = N_e$) with the results also shown in the same figure. It can be seen that the high-energy particles are primarily hydrogen atoms, not protons, at energies below 60 keV in the case of the completely neutral gas, while the corresponding transition occurs at 25 keV for the case of a half-ionized gas. Thus most of the ionization occurs in collisions with fast hydrogen atoms, and the numerical results given for collisional equilibrium above are not quantitatively correct in detail, since they are based on fast proton cross-sections. Only if the medium is nearly completely ionized do the fast particles remain as chiefly protons down to very low energies (because $\sigma_c(e)$ is small in comparison with the cross-section for ionization).

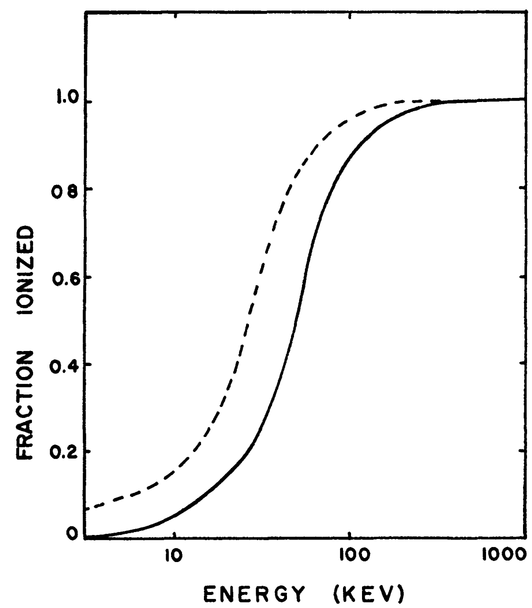

FIG. 4.—Fraction of fast hydrogen particles that are atoms and fraction that are atoms in passing through a gas composed of hydrogen atoms (*solid curve*) or of hydrogen atoms, protons, and electrons in equal numbers (*dashed curve*).

PARTICLE RANGES

A further problem is the energy loss and range of high-energy particles in the interstellar matter. The loss of energy E per unit path length s by a fast particle may be written

$$\frac{dE}{ds} = -N_H\Delta(\mathrm{H}) - N_p\Delta(\mathrm{H}^+) - N_e\Delta(e) \qquad (20)$$

where $\Delta(\mathrm{H})$ is the stopping power of neutral hydrogen, $\Delta(\mathrm{H}^+)$ is the stopping power of ambient protons, and $\Delta(e)$ is the stopping power of ambient electrons, and where we have again schematized the interstellar medium as pure hydrogen, neutral and ionized. Since the high-energy particle may be either a proton or a hydrogen atom with the relative probabilities f^+ and $1 - f^+$, each of these stopping powers may be written

$$\begin{aligned} \Delta(\mathrm{H}) &= f^+\Delta(\mathrm{H}^+, \mathrm{H}) + (1 - f^+)\Delta(\mathrm{H}, \mathrm{H}) , \\ \Delta(\mathrm{H}^+) &= f^+\Delta(\mathrm{H}^+, \mathrm{H}^+) + (1 - f^+)\Delta(\mathrm{H}, \mathrm{H}^+) , \\ \Delta(e) &= f^+\Delta(\mathrm{H}^+, e) + (1 - f^+)\Delta(\mathrm{H}, e) , \end{aligned} \qquad (21)$$

where $\Delta(\mathrm{H}, \mathrm{H}^+)$ is the stopping power of neutral hydrogen for high-energy protons, etc. Of these, $\Delta(\mathrm{H}, \mathrm{H})$ and $\Delta(\mathrm{H}, \mathrm{H}^+) = \Delta(\mathrm{H}^+, \mathrm{H})$ are tabulated by Dalgarno and Griffing (1955), while formulae for $\Delta(\mathrm{H}^+, \mathrm{H}^+)$ and $\Delta(\mathrm{H}^+, e)$ are given by Hayakawa and Kitao

(1956). We have approximately calculated $\Delta(\mathrm{H}, e)$ taking account of the energy loss by excitation, ionization, and elastic scattering. In this approximate calculation the contribution of the excitation to the stopping power has been estimated as the cross-section for excitation of Lα (Seaton 1962*b*) multiplied by 16.5 eV. We use 16.5 eV instead of 10.2 eV, the excitation energy of Lα, to take approximate account of the excitation of other higher levels. The contribution of ionization to the stopping power has been estimated as the ionization cross-section (Geltman, Rudge, and Seaton 1963) multiplied by 27 eV, under the assumption that on the average the freed electron acquires an energy equal to the ionization potential. Finally, the contribution of the elastic scattering due to energy loss is the elastic-scattering cross-section (Moiseiwitsch 1962) multiplied by $2m\,E/M$, where m and M are the electron and proton mass, respectively. The energy losses by high-energy particles passing through a medium consisting of hydrogen 50 per

TABLE 3

STOPPING POWER OF A HALF-IONIZED ATOMIC HYDROGEN GAS

$(N_{\mathrm{H}} = N_p = N_e)$

log E (keV)	$(1-f^+)/f^+$	$\Delta(\mathrm{H}^+, e)$ (eV cm²)	$\Delta(\mathrm{H}, \mathrm{H}^+) = \Delta(\mathrm{H}^+, \mathrm{H})$ (eV cm²)	$\Delta(\mathrm{H}, \mathrm{H})$ (eV cm²)	$\Delta(\mathrm{H}, e)$ (eV cm²)	Δ (eV cm²)
3 5	3 2$\times10^{-8}$	4 4$\times10^{-15}$	0 46$\times10^{-15}$	0 62$\times10^{-15}$		2 4$\times10^{-15}$
3 0	6 5$\times10^{-6}$	1 3$\times10^{-14}$	1 2 $\times10^{-15}$	1 6 $\times10^{-15}$	. .	7 4$\times10^{-15}$
2 5	7 6$\times10^{-4}$	4 0$\times10^{-14}$	2 7 $\times10^{-15}$	3 8 $\times10^{-15}$	7 9 $\times10^{-15}$	2 2$\times10^{-14}$
2 0	3 8$\times10^{-2}$	1 2$\times10^{-13}$	6 2 $\times10^{-15}$	5 5 $\times10^{-15}$	9 6 $\times10^{-15}$	6 2$\times10^{-14}$
1 5	6 2$\times10^{-1}$	3 7$\times10^{-13}$	1 2 $\times10^{-14}$	4 4 $\times10^{-15}$	1 42$\times10^{-14}$	1 2$\times10^{-13}$
1 0	6 0	1 1$\times10^{-12}$	1 3 $\times10^{-14}$	2 8 $\times10^{-15}$	1 15$\times10^{-14}$	1 0$\times10^{-13}$

cent ionized are collected in Table 3, where we have defined the total stopping power of the medium Δ by the equation

$$\frac{dE}{ds} = -N\Delta\,, \tag{22}$$

with $N = N_H + N_p$ = density of hydrogen in the medium, whether neutral or ionized. Note that according to this definition Δ depends on the degree of ionization of the medium, though $\Delta(\mathrm{H})$, $\Delta(p)$, and $\Delta(e)$ do not. Very roughly, this table may be represented by the interpolation formula

$$\begin{aligned} \Delta &= 0.7 \times 10^{-13} \quad \text{eV cm}^2 \text{ for } E < 100 \text{ keV}\,, \\ \Delta &= 0.7 \times 10^{-11}/E \text{ eV cm}^2 \text{ for } E > 100 \text{ keV}\,, \end{aligned} \tag{23}$$

and integration then gives the range $s_0(E)$ a particle with initial energy E may travel before it is stopped completely,

$$\begin{aligned} s_0(E) &= 4 \times 10^{-3}\, E/N & &\text{for } E < 100 \text{ keV}\,, \\ s_0(E) &= [2 \times 10^{-5}(E^2 = 10^4) + 4 \times 10^{-1}]/N & &\text{for } E > 100 \text{ keV}\,, \end{aligned} \tag{24}$$

where in both equations (23) and (24) E is expressed in keV, and s_0 in pc. It can be seen that if the ambient medium has density $N = 10^2$ particles per cm³, representative of NGC 1068, the range of a 100-keV particles is only about 0.004 pc, the range of a 1-MeV particle, about 0.2 pc, and the energy necessary for a particle to have a range of 50 pc, the radius of the nucleus of NGC 1068, is about 15 meV. Thus, if fast particles were the ionization mechanism in NGC 1068, and if these particles came from a single source at the center of the nucleus, they would have to have an energy of 15 MeV or more to have sufficient range to ionize all of the observed gas. The presence of such high-energy particles, however, would cause ionization to a much higher degree than the highest observed, Ne^{+4} and Fe^{+6}, and in particular [Fe x] lines would be observed. Since this ion is not observed we must conclude that there is no appreciable flux of high-energy particles with $E \geq 10$ keV, and therefore that there cannot be a single source of high-energy particles responsible for ionizing the entire nucleus. However, it is quite conceivable that there are many sources of high-energy particles with energies up to 20 keV; in fact the observed velocities shown by the Doppler widths of the emission lines are around 2000 km/sec, corresponding to 20 keV and may be regarded as the consequence of cloud motions. In the collisions between these clouds the kinetic energy of mass motions may be converted into ionization energy in layers a few thousandths of a parsec thick, the range corresponding to 20–30-keV initial energy.

It is appropriate to examine the predicted line intensities under conditions of collisional ionization by high-energy particles to see whether any significant observable differences are expected from the spectrum produced under the conditions of

TABLE 4

CROSS-SECTIONS FOR COLLISIONAL EXCITATION OF Hα AND FOR COLLISIONAL IONIZATION BY HIGH-ENERGY PROTONS AND H ATOMS

PROTON CROSS-SECTIONS			H-ATOM CROSS-SECTIONS		
E (keV)	$\sigma(H\alpha)/\pi a_0^2$	$\sigma(ion)/\pi a_0^2$	E (keV)	$\sigma(H\alpha)/\pi a_0^2)$	$\sigma(ion)/\pi a_0^2$
10	0 40	1 59	10	0 063	0 20
100	23	1 52	31 6	0 050	0 27
1000	0 043	0 20			

radiative ionization ordinarily in effect in gaseous nebulae. In both cases the electrons produced by ionization are thermalized and produce an emission-line spectrum due to recombinations and to thermal collisional excitation. Thus the only possible sign of the high-energy particles would be their effect in direct collisional excitation of emission lines. High-energy particles are known to be most effective in exciting optically permitted transitions (see, e.g., Bates 1962), and we therefore examine the case of the Balmer-line spectrum of hydrogen, using the excitation and ionization cross-sections calculated by Bates and Griffing (1953). The nucleus of NGC 1068 presumably fulfils well the "case B" condition of being optically thick in Lyman-line radiation, so that every excitation of a hydrogen atom to the state $n = 3$ is followed ultimately by emission of an Hα photon. We therefore list in Table 4 the cross-sections for excitation of this level by protons and by H atoms of various energies, and compare it with the cross-section for ionization by these same particles. Since every ionization is followed ultimately by a recombination, and since under case B conditions about 0.4 of the recombinations lead to emission of an Hα photon (Seaton 1960), the cross-section for ionization followed by emission of an Hα recombination photon is 0.4 σ (ion). Thus from Table 4 we see that ionization followed by recombination is considerably more effective for the emission of Hα than direct collisional excitation, and we can expect only minor modification of the predicted Hα intensity to result from collisional excitation due to high-energy particles. Since the collisional excitation cross-sections drop off rapidly with increasing n (Bates and Griffing 1953), the same conclusion holds even more strongly for Hβ, Hγ, etc.

In the case of helium, the singlet upper levels are expected to be most strongly excited by collisional excitation by fast particles (Bates 1962), and the best possibility is probably the 2^1S–3^1P λ 5016 line, which unfortunately is very close to the strong [O III] λ 5007 line. According to the experimental (Hughes, Waring, and Fan 1961) and theoretical (Bell 1961) collisional excitation cross-sections, however, this line should be a factor of 10 weaker than the recombination line λ 5876, and since the latter line is just barely measurable in NGC 1068 there is no hope of detecting the collisionally excited lines of helium in this nebula. We can therefore not make a direct test of the collisional excitation mechanism.

Another possibility for the ionization mechanism in NGC 1068, since it is the nonthermal radio source 3C 71, is that the synchrotron spectrum may continue to the ultraviolet and provide the ionizing photons, as in NGC 1952 (Woltjer 1958) and possibly also in M 82 (Lynds and Sandage 1963; Sandage and Miller 1964). Although, as we have seen above, the observation that neutral and ionized material are intimately mixed in NGC 1068 rules out the possibility that the ionization might come from a single point source of ultraviolet photons, if the magnetic field and high-energy photons were dispersed throughout the gas in the nucleus, each emitted ultraviolet synchrotron photon would be absorbed near its point of origin, and the ionized and neutral material could be contiguous.

The far-ultraviolet synchrotron radiation is completely unobservable, and we can only estimate its amount by an extrapolation from the observable region. We shall suppose that the synchrotron spectrum has the form

$$S(\nu) \propto \nu^{-a} \tag{25}$$

all the way from the radio-frequency region to the ionizing ultraviolet; it is known that this spectrum results if the emitting electrons have a power-law spectrum energy

$$N(E) \propto E^{-(2a+1)} . \tag{26}$$

Because of radiation losses, the high-energy electrons tend to decay fastest, and an initial electron-energy spectrum of the form of equation (25) at a later time falls off more rapidly at energies $E > E_c$, the cut-off energy, with the result that the emitted synchrotron spectrum falls off more rapidly than equation (24) indicates at frequencies $\nu > \nu_c \simeq 10^{13}\, H\, E_c^2$, the cut-off frequency (Oort and Walraven 1956), with E in BeV. Our assumption thus is that the cut-off frequency is well above the Lyman limit, $\nu_0 = 3.29 \times 10^{15}$ sec^{-1}, that is the power-law spectrum of electron energies continues up to well above 10^3 BeV, and is made for the purpose of finding an upper limit to the possible effects of the ultraviolet synchrotron radiation.

According to the recent compilation of Kellermann (1964) over the range from 38 Mc to 3000 Mc, the observed radio-frequency spectrum of NGC 1068 can be represented by equation (25), with $a = 0.59 \pm 0.03$, and the flux at 400 Mc is $10.4 \pm 0.3 \times 10^{-26}$ watts/m^2 cps $= 1.04 \times 10^{-22}$ erg/cm^2 sec cps. Therefore if the power-law equation (26) holds to frequencies well above the Lyman limit the emitted flux at this frequency that would be received at the earth is $S(\nu_0) = 8.6 \times 10^{-27}$ erg/cm^2 sec cps, and the total flux of ionizing photons with $\nu > \nu_0$ is

$$\int_{\nu_0}^{\infty} \frac{S(\nu)\, d}{h\nu} = \frac{S(\nu_0)}{a h} = 2.2\, \frac{\text{photons}}{\text{cm}^2\ \text{sec}} \tag{27}$$

at the earth.

If we assume that every one of the ionizing photons is absorbed by the gas in the nucleus of NGC 1068, each causes one ionization of an H atom, which is balanced by a recombination, and if all the recombinations to levels $n \geq 3$ lead ultimately to emission of an Hα photon, then the predicted Hα flux at the earth is thus 1.4 photons/cm^2 sec or 4.2×10^{-12} erg/cm^2 sec, since under case-B conditions about 65 per cent of the effective recaptures occur to $n \geq 3$ (Spitzer 1948). The observed Hα flux is 1.6×10^{-11} erg/cm^2 sec, and the conclusion is that if the synchrotron spectrum continues with unchanged spectral index to the far ultraviolet, there are insufficient ionizing photons to explain the observed intensity of Hα.

Further, it seems unlikely on geometrical grounds that all the ionizing photons emitted in the synchrotron process can be absorbed by the gas in the nucleus of NGC 1068. For this to occur, the high-energy electrons would have to be confined within the nucleus, but as Greenstein and Schmidt (1964) have pointed out in the case of the quasi-stellar radio sources 3C 48 and 3C 273, the free-free transitions make the gas optically thick to radio-frequency radiation. Their equation (46) shows that the nucleus of NGC 1068 is optically thick for all radiation with $\nu \leq 200$ Mc, and therefore if the high-energy electrons were confined to the nucleus, a thermal spectrum would be observed in this same band, but in fact the observations show that the non-thermal spectrum continues down to 38 Mc (Kellermann 1964). Therefore we must conclude that a considerable amount of the synchrotron emission occurs outside the gaseous nucleus, and hence that only a fraction of it can be absorbed in the nucleus.

Direct observational evidence must come from high-resolution radio measurements of NGC 1068. The Caltech interferometer measurements at 1000 Mc give only an upper limit to the size of the radio-emitting region, namely, that its diameter is smaller than 30″ Maltby, Matthews, and Moffet 1963). The Manchester interferometer measurements at 158 Mc show a decrease in visibility at large spacings that leads to a diameter, if the object is interpreted as a circular Gaussian source, of 9″ (Allen, Brown, and Palmer 1962). Since the optical diameter of the nucleus is 2″ (Woltjer 1959), the average dilution factor is $r^2/4R^2 = 0.012$, and taking this into account the synchrotron photons would be quite insufficient to explain the observed ionization, even if the spectral index does not decrease between the radio region and the Lyman limit. However, the interferometer measurements are not detailed enough to map out the synchrotron source, so it is possible that it is concentrated just outside the optically thick nucleus, in such a way that the dilution factor is larger than the estimate above. Until further radio observations are available, this question will remain open, but on the basis of the present evidence the importance of photoionization by ultraviolet synchrotron radiation as extrapolated from the radio data seems to be small.

Note added in proof: More recent high angular-resolution radio observations of NGC 1068 = 3C 71 at 610 Mc/s (Adgie 1964) show that the diameter of the radio-emitting region is 10″ and thus confirm the dilution factor used above.

One further possibility for evaluating the importance of photoionization by synchrotron radiation is provided by the ultraviolet measurements listed in Table 2. As Walker (private communication) first noticed, and as these measurements confirm, the nuclear region of NGC 1068 is usually bright in the ultraviolet. There is not much published information on spectral scans of the nuclei of spiral galaxies, but from the information given by Code (1959) and Oke (1962, 1964*b*) it appears that in NGC 1068 the ratio F_ν (λ 3600)/F_ν (λ 4250) for instance is much higher than expected in the centers of spiral galaxies. Thus much of the ultraviolet radiation from this object can be considered as excess radiation over that expected from stars in the nucleus, and it might arise from synchrotron radiation. The expected amount of synchrotron radiation, extrapolating from the radio measurements by equation (25) with the value $\alpha = 0.59$ used above predicts a flux $F_\nu = 2\,5 \times 10^{-26}$ erg/cm^2 sec c/s in the range λ 3600–λ 3300. Thus the observed ultraviolet flux, F_ν (λ 3600) $= 3.0 \times 10^{-25}$ erg/cm^2 sec (c/s), is about ten times that predicted as the upper limit to the synchrotron radiation, which suggests the possibility that the synchrotron spectrum might curve up in the ultraviolet, and there might therefore be more ionizing radiation (with $\lambda < 912$ Å) than the upper limit given by equation (25) and assumed in the calculations above. This would tend to increase (by a little more than a factor of 10) the number of ionizing photons, and thus to reduce the discrepancy in the ionization calculation by a similar factor. However, according to the radio-frequency measurements of Conway, Kellermann, and Long (1963) and Kellermann (1964), there are no sources known in which the spectrum decreases in curvature toward shorter wavelengths in the radio-frequency region, nor is there any optical evidence for such a decrease in curvature of the synchrotron spectrum toward shorter wavelength in other radio sources studied to date (O'Dell 1962; Matthews and Sandage 1963; Lynds and Sandage 1963). Thus it seems unlikely that all the observed ultraviolet radiation in NGC 1068 is synchrotron radiation, and in fact the observed amount can be understood as a result of two-photon emission of neutral hydrogen, excited by fast protons, if we adopt the collisional ionization mechanism (see Appendix B).

Our final conclusion is that the ionization and heating mechanism in the nucleus of NGC 1068 can be understood as a result of collisions between rapidly moving gas clouds. It can also just possibly be understood to result from ultraviolet synchrotron radiation, if the synchrotron-emitting electrons are closely concentrated around the nucleus and if the synchrotron spectrum decreases less rapidly to the ultraviolet than the radio observations, extrapolated, would precict. The collisional mechanism seems more likely to be correct, but it is not certain.

We are indebted to Dr. M. F. Walker for his unpublished observational results on NGC 1068; to Dr. J. B. Oke for his unpublished results on the energy distributions of galaxies; and to Dr. W. L. W. Sargent for his unpublished thesis which discusses theoretically many of the problems of heating and ionization involved in collisions of gas clouds. We are also indebted to Mr. J. L'Eucyer and Mr. J. Marlborough for help with the observational data. We are also grateful to the Mount Wilson and Palomar Observatories for the opportunity to work there as guest investigators during the summer of 1964, when this paper was composed, and to the National Science Foundation for the support of one of us during that period, and to the Space Astronomy Laboratory at the University of Wisconsin for the opportunity to carry out most of the theoretical calculations on the IBM 1620.

APPENDIX A

ESCAPE OF He II Lα PHOTONS

Our discussion of the ionization based on the Bowen resonance-fluorescence lines of O III might be thought to be vitiated by the large internal velocity dispersion of NGC 1068, which tends to decrease the line-absorption coefficient and thus to allow He II Lα photons to escape more freely. This is not correct, however, for a photon is emitted with a thermal distribution of frequencies corresponding to the point at which it is emitted, and the "turbulent" velocities have to be taken into account only if it is absorbed at a place where the velocity of mass motion is different from the velocity at the place where the photon was emitted. For a He^+ ion at $T = 10^4$ degrees, the central line-absorption coefficient taking account of thermal motions only is 2.9×10^{-14} cm^2 and so at an assumed electron density $N_e = 10^4$ cm^{-3}, corresponding to an ionized helium density approximately $N(He^+) = 10^3$ cm^{-3}, the mean free path for a photon at the center of the line is about 3×10^{10} cm, or for an average photon in the line, perhaps 8×10^{10} cm $= 3 \times 10^{-8}$ pc. This length, about 1 solar radius, is so small that the turbulent difference in velocity from one end of it to the other must be small, and the conclusions are that the thermal line-absorption coefficient is essentially correct and that photons do not escape because of the large turbulent velocities, which must occur over considerably larger dimensions.

APPENDIX B

THE BALMER EMISSION LINES IN NGC 1068

The observed relative strengths of the Balmer lines in the nucleus of NGC 1068, $H\alpha/H\beta/H\gamma/H\delta = 12.5/1/0.3/0.07$ is steeper than predicted by any physical theory. Recombination theory predicts Hα/Hβ around 3/1 (Seaton 1960), and thermal-electron collisional excitation predicts high Hα/Hβ ratios only for such low temperatures that the degree of ionization and the emission rate are very small (Parker 1964). Therefore, in NGC 1068, where there is considerable ionized gas, the recombination emission should dominate unless there are exceedingly large amounts of neutral hydrogen. Furthermore direct collisional excitation by fast protons is not effective enough to appreciably modify the Balmer decrement expected from recombination, as shown above. One possible explanation is simply observational error, and this may affect Hγ and Hδ, which are weak lines observed on underlying absorption lines in the spectrum of the galaxy, but Hα and Hβ are so strong and the discrepancy so large that we believe observational error cannot be the explanation of the Hα/Hβ ratio About the only possibility remaining is that the relative intensities are modified by self-absorption. At an electron density $N_e = 10^4$ cm^{-3}, the numbers of H atoms in the $2s$ and $2p$ states, respectively, as a result of ionization followed by recapture are approximately $N(2s) = 10^{-6}$ cm^{-3} and $N(2p) = 3 \times 10^{-14} Q$ cm^{-3}, where Q is the average number of scatterings a typical Lα photon suffers (Osterbrock 1964). If $Q \leq 10^7$, the situation in typical gaseous nebulae, $N(2s) > N(2p)$, and the central line-absorption coefficient, taking account only of thermal broadening, is 3.3×10^{-13} cm^2. The mean free path of an Hα photon in the center of the line is thus about 3×10^{18} cm $= 1$ pc, and over this distance there may be reasonably large turbulent velocity differences, so the actual mean free path is even larger. The radius of the whole nucleus is about 50 pc; of this volume, however, only 10^{-3} contains ionized gas at the assumed density $N_e = 10^4$ cm^{-3}, so the total effective length in the ionized gas is only 5 pc, and the self-absorption effects are expected to be small. However, if there are large amounts of neutral gas present between the clouds of ionized gas, then the Lα photons can be trapped for very large numbers of scatterings Q, and the self-absorption may be much higher, sufficient to modify the Balmer decrement appreciably. Much more detailed calculations would be necessary to justify or disprove this suggestion.

We might note, however, that if the mechanism of ionization is by collisions with high-energy protons, then we expect a very large additional excitation rate of the $2p$ and $2s$ levels of neutral H because of the resonance contributions to the cross-sections (Bates and Williams 1964; Lovell and McElroy 1964). For instance, assuming the fast-particle power-law spectrum (equation 12) with $\gamma = 2$ extends down to low energy (or the order of 30 eV), then using the cross-section for excitation of $2p$ by protons approximately calculated by Bates and Williams (1964), the rate of excitation of $2p$ and hence of Lα is 50 times as large as the rate of ionization calculated according to equation (11). Since every ionization is followed by recombination leading ultimately to emission of Lα, this means the rate of emission of collisionally produced Lα is 50 times as large as the rate of recombination-produced Lα, and the population $N(2p)$ is higher by a corresponding factor, thus greatly enhancing the self-absorption effects discussed above. Incidentally, the ratio of emission in Lα to Hα (by number of photons) is thus about $50/0.4 = 200$ under pure case B conditions, and somewhat less, about 100, if the higher Balmer lines are self-absorbed as we assume, so NGC 1068 and other similar objects should be very bright in Lα.

Collisional excitation of $2s$ is less important, but extrapolating the approximate calculations of cross-sections of Lovell and McElroy (1964), which extend down to only 1 keV energy, it appears that with the $\gamma = 2$-proton energy spectrum there might be 5 proton-induced excitations of $2s$ per proton-induced ionization. The numerical results for the excitation of $2s$ and $2p$ are, of course, heavily dependent on the exact form of the proton energy spectrum at low energies.

Finally we can estimate the rate of emission in the 2-photon continuum (Spitzer and Greenstein 1951) resulting from the above rate of excitation of $2s$. According to it, there are about 10 excitations of $2s$ per excitation (by ionization followed by recombination and self-absorption) of Hα. At densities $N_e \lesssim 10^4$ per cm^3, most of the excitations to $2s$ are followed by emission of two photons in the continuum, with energy totaling $27/5 = 5$ 4 times energy of a single Hα photon. Hence from the observed flux in Hα at the Earth, 1.6×10^{-11} erg/cm^2, we deduce that the expected flux in the whole 2-photon continuum at the Earth is $10 \times 5.4 \times 1.6 \times 10^{-11} =$

8.7×10^{-10} erg/cm² sec. Of this total flux, the flux per unit frequency interval at $\nu = y\nu_{12}$, where $\nu_{12} = 2\ 46 \times 10^{15}$ c/s is the frequency of Lα, is easily shown to be

$$F_\nu = \frac{y\psi(y)}{\frac{1}{2}\int_0^1 y\psi(y)\,dy\nu_{12}} F(\text{2-photon}) \tag{B-1}$$

in the notation of Spitzer and Greenstein (1951) In the near ultraviolet, specifically at μ 3500 Å, the expected flux in the 2-photon continuum is thus found to be 3.1×10^{-25} erg/cm² sec c/s, in good agreement with the total observed flux given in Table 2 The conclusion is that all the observed ultraviolet radiation from the nuclear region of NGC 1068 can be approximately accounted for as 2-photon continuum excited by fast-proton collisions with neutral H, if the proton-energy spectrum with $\gamma = 2$ extends down to low energies.

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