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UNPUBLISHED PRELIMINARY DATA

IONIZED GAS IN THE NUCLEI OF ELLIPTICAL, SO,

SPIRAL, AND IRREGULAR GALAXIES*

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ABSTRACT

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The intensity ratio of the emission lines Hα and [N II] λ6583 is a sensitive indicator of T_e and the mode of excitation in interstellar gas. E and S0 galaxies in which interstellar gas is known to be present from the occurrence of [O II] λ3727 have been surveyed in the red spectral region, and the results, together with a summary of similar observations in the nuclei of spirals and irregulars, are presented. A total of 85 galaxies has been examined. In E and S0 galaxies usually only [N II] λ6583 was seen. Among galaxies showing emission lines in the red, the intensity ratio Hα/[N II] λ6583, which is ~ 3 in spiral arms, is ≤ 1 in 100% of the ellipticals, in 81% of the S0, and in 55% of the nuclei of spirals. This ratio is ≥ 3 in 100% of the nuclei of irregulars. The most probable explanation of this effect is that in those nuclear regions where K giants provide most of the radiation, the gas is heated to $T_e \sim 10000° - 20000°$; the energy which is fed into the gas is kinetic and not radiative in origin, and comes from evolutionary mass loss from M 67-type K giants moving with large random velocities. Alternatively, the N abundance may be higher than normal through the products of nuclear reactions in evolved stars.

I. INTRODUCTION

In 1962 we published a study of the emission lines arising in the ionized gas in a considerable number of spiral and irregular galaxies (Burbidge and Burbidge 1962a). The lines most commonly seen in the red region of the spectrum are Hα and [N II] λ6583. We showed that the intensity ratio Hα/[N II] λ6583 varies in a systematic way in a large number of spiral galaxies in the sense that this ratio is of the order of 3 in the spiral arm regions and decreases and often reaches a value as low as 0.1 or less in the central parts. In a theoretical investigation (Burbidge, Gould, and Pottasch 1963) it was shown that the reversal of this ratio in the central bulge was probably due to the fact that the gas there is heated by the dissipation of kinetic energy and excited by electron collisions. It was suggested that the energy providing the excitation comes ultimately from gas that has been ejected from the cool stars which form the bulk of the stellar population in the central regions of those galaxies where the reversal occurs.

After we unexpectedly discovered this effect in the Sb and Sc spirals which we were studying for rotations and velocity fields, we thought it worthwhile to investigate whether similar effects were present in Sa, SO, and elliptical galaxies. It is well known that in these galaxies there is very much less evidence for the presence of interstellar matter in the form of either neutral gas, ionized gas, or dust, than in the spirals and irregulars. Moreover, when there is ionized gas present it is usually located near the center and is not detected in the outer parts of such galaxies; exceptions are the very peculiar systems like the radio galaxy NGC 5128, and the Sa galaxy NGC 681 which was investigated as a result of the present study (Burbidge, Burbidge, and Prendergast 1965), since it was discovered to contain as much ionized gas as an Sc galaxy.

II. OBSERVATIONS

The red spectral region was therefore photographed in a selection of all the Sa, SO and elliptical galaxies in the catalogue of Humason, Mayall, and Sandage (1956) in which [O II] $\lambda3727$ had been found, with exposures suitable for showing the central regions only. As Osterbrock (1960) has pointed out, these galaxies are denoted in Tables 1 and 2 of Humason et al. by asterisks and double-primes following the spectral types; by accident the meaning of these signs was omitted from their paper. Our observational program was conducted with the B-spectrograph attached at the prime focus of the 82-inch McDonald telescope, during the period 1959-1963. A total of seventy-one spectra were obtained of forty-one galaxies, of which thirteen were E, nineteen were SO, and nine were Sa. One of the spectra which we shall discuss (of NGC 5195) was obtained with the Lick prime focus spectrograph.

We chose predominantly galaxies in which [O II] $\lambda3727$ had already been found because in the first instance we wanted to be sure that some ionized gas was present. However, the spectra obtained by Humason were taken over a long time period with several telescopes and spectrographs and were obtained primarily to measure redshifts. Thus optimum exposures to detect [O II] $\lambda3727$ were often not made, so it is not clear that the galaxies in which this emission line has been detected are the only ones in which it <u>can</u> be detected. There are some systems in which [N II] $\lambda6583$ is seen and there is no evidence for the presence of [O II] $\lambda3727$. There are also systems which are not listed as having [O II] $\lambda3727$ in the catalogue of Humason et al. but in which it is now known to be present, often with other emission lines (e.g. NGC 4438). However, we have taken a fair sample of those galaxies in which we have evidence for the presence of ionized gas, restricting ourselves to the brighter galaxies and omitting all anonymous objects with fairly large redshifts.

As this investigation proceeded, it became clear that the Sa systems formed a very heterogeneous group, with more affinity to the Sb and Sc systems studied earlier than to the SO and E galaxies. For making this statistical study, therefore, we shall include the results obtained earlier on the nuclei of all types of spirals and irregulars, together with some additional material in Sb and Sc galaxies obtained since 1962.

The problem of detecting Hα and [N II] λ6583 in the nuclear regions of galaxies is more difficult than that of finding [O II] λ3727 because the continuum in the red due to the integrated continuous background from the late-type stars in a galactic bulge is very much stronger than it is in the ultraviolet around 3700 A. Therefore it was necessary to take under-exposed spectra; exposures of only 10 - 20 minutes often were found to be appropriate. Moreover, because of the characteristically very steep light distributions in these galaxies, short-exposure spectra taken in good seeing are exceedingly narrow and under these conditions emission lines are difficult to detect. Thus this program is best carried out in conditions of poor seeing, a unique situation in extragalactic research. As is shown in Tables 1 and 2, we have found emission features in a number of SO and E galaxies, although often only one line is seen. The only way we have of determining whether this is Hα or [N II] λ6583 ([N II] λ6548 is weaker than λ6583 and is less likely to be seen) is to measure the wavelength of the feature and determine two redshifts, assuming that it is either Hα or [N II] λ6583, and then to compare the redshifts so obtained with the redshifts measured from absorption lines and λ3727 by Humason et al. Since the wavelength difference of 20 A between Hα and [N II] λ6583 corresponds to 940 km/sec, this is easily done.

III. RESULTS

In Table 1 the elliptical galaxies which have been studied are listed. These include all of the field and Virgo Cluster galaxies classified as ellipticals in which Humason has detected [O II] λ3727, with the following one addition and three omissions. NGC 821 is included and in this system no [O II] λ3727 was detected by Humason, and we could not detect Hα or [N II] λ6583. NGC 4486, NGC 5846, and NGC 5128 (classified Ep) are not included. Of these, NGC 4486 and NGC 5128 are both systems in which we believe that violent activity has taken place in their nuclei (Burbidge, Burbidge, and Sandage 1963). It is almost certain that NGC 4486 shows emission in the red, but we have not examined it. NGC 5128 has been the subject of detailed studies (Burbidge and Burbidge 1959, 1962b). It shows [O II] λ3727, Hα, and [N II] λ6583, but its nucleus is obscured by dust and we have not thought it appropriate to include it here. NGC 5846 shows no abnormality and Humason has detected [O II] λ3727 in it but we have not obtained spectra in the red. One of the galaxies, NGC 4278, was not observed by us; we have included here the data taken from Osterbrock (1960).

The first column gives the NGC number, and the second the type. Throughout this paper, we give types on the Hubble system, mainly taken from Humason et al. (1956) or the Hubble Atlas (Sandage 1961); a few are revisions or new classifications which we have made. Columns 3 and 4 show whether Hα and [N II] λ6583 are seen on our spectra; a "p" denotes their presence and a dash shows that the line in question was not visible on our spectra. Column 5 gives the intensity ratio Hα/[N II] λ6583. When only [N II] λ6583 is seen, this ratio is simply given as < 1; it could in fact have any value from just less than unity to zero.

Columns 6, 7, and 8 give, respectively, our measured redshift, that by Humason from Tables 1 or 2 of Humason et al., and that by Mayall from Table 5 of the same paper. These are given because they provide the only means of checking, when only one emission line was seen, whether the line is Hα or [N II]. Our redshifts are not of great accuracy, since they have often been derived from only one weak and rather broad emission line measured on either one or two spectra. In general, however, there is quite good agreement. Discrepant velocities are discussed in the footnotes, which also give information on other lines seen in the spectra and on velocity gradients due to rotation of the galaxies.

In Table 2 the SO galaxies studied are given. These include seventeen galaxies listed as showing [O II] λ3727 emission by Humason et al. There are ten more systems in this category listed by Humason et al. as showing emission which we have not examined, because of limitations in the amount of observing time available and the fact that we feel these form a sufficient sample. In addition to these we have listed two more systems, NGC 1316 and NGC 4438, in which we have found emission in the red spectral region in the nucleus, though Humason did not detect emission in either galaxy. NGC 1316 is the galaxy associated with the radio source, Formax A. The columns in Table 2 are arranged in the same way as thos in Table 1.

The Sa galaxies are given in Table 3, where we have also collected the information on the nuclei of galaxies of types Sb, Sc, and irregular. Some of this information was scattered through the paper by Burbidge and Burbidge (1962), and some comes from spectra used in obtaining rotation-curves and velocity fields since that date. Redshifts are not given in Table 3, since most have been published previously and most galaxies show both Hα and [N II] λ6583, so that there is no doubt about the identification of the lines.

There are twenty-seven Sa galaxies listed by Humason et al. as showing [O II] λ3727; of these, three (NGC 4151, 5548, and 7469) are Seyfert galaxies which fall into the category of abnormal galaxies showing the results of violent nuclear events. One more, NGC 2146, is better classified as Sbp, and is in the Sb section of Table 3. The ten Sa galaxies given in Table 3 are a big enough sample to show that, as regards the occurrence and relative intensity of Hα and [N II], these objects are more closely related to the other spirals than to the SO and ellipticals.

For the fourteen ellipticals listed, thirteen show evidence for the presence of ionized gas in the nucleus and two of these show no emission lines in the red spectral region. Of the eleven that do, nine show only [N II] λ6583, while in two more, Hα/[N II] λ6583 is, respectively, < 1 and $= 1$. Thus in all these eleven cases, Hα/[N II] λ6583 ≤ 1.

For the nineteen SO galaxies there is evidence in all for the presence of ionized gas in the nucleus, but three show no emission lines in the red spectral region. In eleven galaxies only [N II] λ6583 is seen, so that the ratio Hα/[N II] λ6583 < 1. In thirteen galaxies Hα/[N II] λ6583 ≤ 1.

Of the ten Sa systems in Table 3, which all show the presence of ionized gas in the nucleus, only two have Hα/[N II] λ6583 < 1. In one other system, Hα/[N II] λ6583 $= 1$, and in three galaxies we can detect no emission in the red spectral region.

In the nuclei of the twenty-one Sb galaxies in Table 3, two have no emission lines in the red, seven have Hα/[N II] λ6583 < 1, four more have this ratio equal to one. For the fifteen Sc galaxies, the nuclei of fourteen show emission lines in the red, of which only one has Hα/[N II] λ6583 < 1 while seven have this ratio equal to 1. All the irregulars have Hα/[N II] λ6583 ≥ 3 in their nuclei as well as throughout the whole object.

This investigation shows very clearly that where ionized gas can be detected in elliptical and SO galaxies, in the very large majority of cases [N II] λ6583 is stronger than Hα. The percentages of those E, SO, spirals, and irregulars showing emission lines in the red, in which [N II] λ6583 is either stronger than or equal to Hα, are given in Table 4. The progression is very obvious.

IV. DISCUSSION

These results support our earlier conclusion that the ratio of the strengths of Hα and [N II] λ6583 is largely determined by the stellar population which is responsible for the excitation of the gas and that two different effects are at work in the galaxies. When gas is present in the spiral arms the main energy input is ultraviolet radiation from the high-luminosity O and B stars and the average Hα/[N II] λ6583 ratio is about 3 as is the case for spiral arm regions of our own Galaxy. In the irregular galaxies, and in a considerable fraction of the spirals, the energy input in the central regions is also radiation from hot stars. However, in the SO and elliptical galaxies and in the central bulges of a large number of spirals the ratio Hα/[N II] λ6583 ≤ 1, and, as has been discussed in earlier papers (Burbidge and Burbidge 1962; Burbidge, Gould, and Pottasch 1963), unless the abundance ratio of nitrogen to hydrogen is higher than normal, such low ratios can be obtained only for values of the electron temperature $\approx 10000 - 20000°$ (Burbidge, Gould, and Pottasch 1963, Fig. 2). We have discussed before the possible sources of energy to maintain this high value of T_e. The results of this paper, which show that the gas in elliptical and SO galaxies, when it is present, shows the same effect in the large majority of cases, may throw further light on the mechanism.

There are two problems involved here. The first concerns the origin of the gas which is seen, and the second concerns its mechanism of excitation. As far as the origin of the gas is concerned, it probably consists of two components, gas which never condensed into stars, or which was ejected by rapidly evolving stars in the early stages of evolution of the galaxy (and possibly ejected in explosions involving massive objects much later) and gas which has been ejected by stars of comparatively low mass in the course of their evolution. These are the K and M giants for which there is direct evidence in a few cases for mass loss (Deutsch 1961). Such mass loss takes place at comparatively low velocities, and if the kinetic energy for the excitation is to arise simply from mass ejection from a star which is at rest relative to the medium it is to excite, then we showed that high velocities of mass ejection (several hundred km/sec) are required, which might be an enhanced "solar wind" type of phenomenon. However, we know that in the central parts of these galaxies the stars have quite high random motions which certainly are of the order of several hundred km/sec. Gas which is ejected from stars with such high random motions will dissipate its kinetic energy in collisions with gas which is already present and it is easy to show that the amount of energy dissipated in this way, assuming the rates of mass loss discussed in our earlier work, may be quite adequate to maintain the excitation at the level at which we believe that it is, as measured from the intensity ratio of these two lines.

The source of energy in this case does not come ultimately from the nuclear energy of the stars, but is the internal energy of the galaxy. Characteristic values for the kinetic energies of the stars in nuclear regions are 2.5×10^{57} - 2.5×10^{58} ergs (10^9 - 10^{10} stars of solar mass with random velocities ~ 500 km/sec). If the rate of cooling through the lines is $\sim 10^{39}$ - 10^{40} erg/sec, then the characteristic time for a nucleus to be cooled by this process is $\sim 10^{11}$ years. Thus the cooling mechanism by itself is not likely to give rise to any drastic speeding up of the rate of evolution of the galaxy. An estimate of the rate of mass loss from the stars can be made. If an equilibrium situation has been reached then we may take the rate of dissipation of kinetic energy equal to the rate of cooling through the lines. This we might put as $-dE_{kin}/dt = 10^{40}$ erg/sec, and if $\langle v \rangle = 500$ km/sec, $-dM/dt \approx 4 \times 10^{24}$ gm/sec. Thus the average mass loss per star has to be 6×10^{-12} $M_{\odot}$/year. This is about 10^{-3} of the mass loss rate obtained by Deutsch for some of the bright M giants. Thus, provided such stars comprise $\sim 0.1\%$ of the total number in the stellar population of a nuclear region, they may be able to supply the kinetic energy required; alternatively a rate of mass loss $\sim 10^{-1}$ of that observed by Deutsch occurring in all of the M 67-type giants would suffice.

One final possibility may be mentioned. In cases where only an upper limit of $H\alpha$/[N II] < 1 can be given because only [N II] λ6583 has been seen, we do not know how low the intensity ratio actually is. If it were much less than 0.1, it would become difficult to explain by varying the electron temperature, because implausibly high temperatures would become necessary (see Fig. 2 of Burbidge, Gould, and Pottasch 1963). We should, therefore, keep in mind the possibility that the N/H abundance ratio is actually higher than normal in gas which has come off evolved red giants. Iben (1965) has recently computed evolved stellar models of red giants in which he suggests that the N abundance on the surface may be higher than normal, because of some mixing following the processing of internal matter in nuclear reactions involving C, N, and O. We suggest that the best way to settle this question is to examine the red spectral region of the nuclei in the best examples of E or SO galaxies with higher resolution than has been done here, to search for $H\alpha$ and determine how small the ratio $H\alpha$/[N II] λ6583 can become.

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Table 1

OCCURRENCE OF Hα AND [N II] λ6583 EMISSION LINES IN ELLIPTICAL GALAXIES

NGC	Type	Hα	[N II] λ6583	Hα/[N II] λ6583	Redshift cΔλ/λ Ours	Humason	Mayall	Footnotes
821	E6	-	-	-				
1052	E3	p	p	1	1458	1439	1523	1
1209	E6	-	p	< 1	2578	2568		
1453	E1	-	p	< 1	3882	3919	4035	2
2749	E2	-	p	< 1	4270	4203		3
2974	E4	-	p	< 1	2008	2013		
3226	E1	-	p	< 1	1444	1338		
3962	E1	-	p	< 1	1843	1794		
4105	E2	-	-	-				
4125	E6	-	p	< 1	1356	1305	1485	
4278	E1	p	p	0.7				4
4550	E7	-	-	-				
4636	E0	-	p	< 1	1000	973	954	
5077	E3	-	p	< 1	2858	2647		5

(1) Emission lines strong; [S II] λλ6717, 6731 and [O I] λ6300 also seen in red. Minkowski and Osterbrock (1959) obtained redshifts of 1572 and 1458 km/sec, respectively, from [O II] and [O III].

(2) [N II] λ6583 extends outside nucleus.

(4) Observations of Hα and [N II] λ6583, and intensity ratio, are taken from Osterbrock (1960); he noted emission very strong, showing [O II], [O III], [Ne III], and Hβ.

(5) Our redshift disagrees with Humason's. [N II] λ6583 is quite weak and broad.

(3) Velocity gradient, due to rotation.

Table 2

OCCURRENCE OF Hα AND [N II] λ6583 EMISSION LINES IN SO GALAXIES

NGC	Type	Hα	[N II] λ6583	Hα/[N II] λ6583	Redshift cΔλ/λ Ours	Humason	Mayall	Footnotes
128	SOp	-	p	< 1	4255	4250		
404	SO	p	p	2	-26	-55		1
1316	SOp	-	p	< 1	1758	1878		2
2655	SOp	-	p	< 1	1517	1299		3
2685	SOp	-	p	< 1	830	884		
2855	SO	-	p	< 1	1913	1908		
2911	SOp	-	p	< 1	3225	3140		
3065	SO	-	p	< 1	1984		2051	
3489	SOp	-	p	< 1	711	692		
3593	SOp	p	p	3	668	547		4
3619	SO	-	-	-				
3718	SOp	-	-	-				
3998	SO	p	p	1	1185	1109	1059	5
4106	SBO	-	-	-				
4374	SO	-	p	< 1	997	954		
4438	SOp	p	p	~ 0.3	321	-32		6
5195	SO	-	p	< 1	606	542		
5866	SO	-	p	< 1	950	740	850	
7679	SO	p	p	2	5174	5202	5101	7

Footnotes for Table 2:

(1) Emission lines strong; [S II] λλ6717, 6731 also seen in red.

(2) Our redshift disagrees with Humason's; perhaps there is a difference in this radio source between absorption and emission lines.

(3) Our redshift disagrees with Humason's. Ours is mean from two spectra which agreed well. Perhaps there is a difference between absorption and emission lines. [N II] λ6583 is very strong, and [S II] is also seen.

(4) Velocity gradient on our two spectra, due to rotation.

(5) Emission lines very strong and broad, like NGC 1052. [S II] λλ 6717, 6731 and [O I] λ6300 also seen in red.

(6) Not noted by Humason as having [O II] λ3727, yet this is seen on the strongest of our spectra which shows the UV region. [S II] λλ6717, 6731 are as strong as [N II] λ6583; [O I] λ6300 also seen and Na I λ5893 is very strong in absorption. This galaxy has extensive dust, partly outside it (Burbidge, Burbidge, and Hoyle 1963). Our redshift disagrees with Humason's; again there may be a difference between absorption and emission lines.

(7) Emission lines very strong; [O III] and Hβ also seen. [S II] λλ6717, 6731 would be redshifted out of observed range.

Table 3

OCCURRENCE OF Hα AND [N II] λ6583 EMISSION LINES IN NUCLEI OF SPIRAL AND IRREGULAR GALAXIES

NGC	Type	Hα	[N II]	Hα/[N II] λ6583	NGC	Type	Hα	[N II]	Hα/[N II λ6583
681[1]	Sa	p	p	1	5383	SBb	p	p	3
1415[2]	Sa	p	p	4	5921	SBb	-	p	< 1
2782[3]	Sa	p	p	3	6951	SBb	p	p	1
3166[4]	Sa	-	p	< 1	7331	Sb	-	p	< 1
3185	SBa	p	p	2	7479	SBb	p	p	< 1
3623	Sa	-	p	< 1	157	Sc	p	p	1
3898	Sa	-	-	-	253	Sc	p	p	1
4314	SBa	p	p	3	925	Sc	p	p	> 3
7727	Sa	-	-	-	1084	Sc	p	p	2
7743	SBa	-	-	-	1385	Sc	p	p	1
613	Sb	p	p	1	1530	SBc	p	p	3
972	Sb	p	p	3	1792	Sc	p	p	1
1097	SBb	p	p	3	2903	Sc	p	p	3
1300	SBb	p	p	1	3198	Sc	p	p	1
1365	SBb	p	p	3	5055	Sc	-	-	-
1398	SBb	-	-	-	5194	Sc	p	p	< 1
1832	Sb	p	p	1	5248	Sc	p	p	3
2146	Sbp	p	p	2	6503	Sc	p	p	1
3066	Sb	p	p	3	6643	Sc	p	p	1
3504	SBb-Sb	p	p	3	7640	SBc	p	p	> 1
3521	Sb	-	-	-	2188	Irr	p	p	> 3
3646	Sb	p	p	3	3034	Irr	p	p	3
4258	Sb	p	p	0.3	3556	Irr	p	p	3
4736	Sb	-	p	< 1	4449	Irr	p	p	> 3
4826	Sb	p	p	0.3	4631	Irr	p	p	> 3
5005	Sb	-	p	< 1	5253	Irr	p	p	> 3

[1] Emission lines extend throughout galaxy; rotation-curve measured (Burbidge, Burbidge, and Prendergast 1965).
[2] Velocity gradient, due to rotation. [N II] λ6583 is very weak, barely visible.
[3] Rotation measured by Duflot-Augarde (1961).
[4] Velocity gradient, due to rotation.

Table 4

PERCENTAGES OF VARIOUS TYPES OF GALAXY HAVING

[N II] λ6583 STRONGER THAN Hα

Hα/[N II] λ6583	E	SO	Spirals	Irregulars
≤ 1	100	81	55	0
< 1	91	69	25	0