INTERSTELLAR MATTER IN ELLIPTICAL GALAXIES. II

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ABSTRACT

Observations are presented of the emission lines resulting from ionized interstellar gas in elliptical
galaxies, together with a preliminary account of their interpretation. The strongest line (with respect to
the continuous spectrum) is the [O III] λ 3727 line, which occurs in different strengths in different galaxies,
down to vanishingly weak intensity. The profile of this line in NGC 4486, the radio source Virgo A, is
broad and double. In NGC 4278, an otherwise typical elliptical galaxy with strong interstellar emission
line, estimates of the mass, rotational velocity, and turbulent velocity of the ionized gas are given, as
well as relative abundances of the observable ions. The mechanism by which the energy that is radiated
in the emission lines is replaced is not known, but it may be either from ultraviolet stellar radiation or
from the conversion of stellar kinetic energy ultimately into heat. It is probable that all elliptical galaxies
contain interstellar gas and that the observed relative strength or absence of emission lines is largely an
effect of ionization. The similarities and differences between the gas cloud in the nucleus of the elliptical
galaxy NGC 4278 and the gas clouds in the nuclei of our Galaxy, of M31, and of M81 are briefly discussed.

I. INTRODUCTION

A small, but not negligible, fraction of elliptical nebulae show the λ 3727 emission
line of [O III] in their spectra, thus indicating the presence in these systems of low-
density ionized gas. The available evidence suggests that interstellar gas, rather than a
large number of planetary nebulae, is the source of this emission (Baade and Mayall
1951; Mayall 1956; Minkowski and Osterbrock 1959), and the appearance of the λ 3727
line in the spectrum of an elliptical galaxy is therefore an indication of the presence of
large H II regions in that object. The origin and evolutionary history of the interestellar
gas in an elliptical is a part of the larger problem of the formation and development of
galaxies, and the present paper is therefore devoted chiefly to observational data bearing
on this subject.

The next section discusses a fragmentary survey of elliptical galaxies for weak and
unreported λ 3727 emission lines. It is followed by a description of the strong and
atypical line profile in the E0 nebula NGC 4486, also well known as the radio source
Virgo A. The rest of the paper deals with observations of the E1 nebula NGC 4278,
chosen for detailed study as an object with a strong, but otherwise apparently normal,
λ 3727 emission line; successive sections deal with the rotation and spatial extent of the
ionized interstellar gas, the random velocities and relative abundances of the elements
in it, and the total amount of gas. Finally, the mechanism of excitation of the emission
lines is discussed, and the probable origin of the interstellar matter is considered.

II. SURVEY FOR WEAK λ 3727 LINES

The published data on the occurrence of λ 3727 emission lines in the spectra of elliptical
galaxies were obtained as by-products of a long-range investigation of the red shifts
of extragalactic nebulae (Humason, Mayall, and Sandage 1956). Of the ellipticals for
which sufficiently well-exposed spectra were obtained so that λ 3727, if present, would
have been detectable, 18 per cent of those observed at Mount Wilson and Palomar Ob-
servatories and 12 per cent of those observed at Lick Observatory did in fact show the
line (Mayall 1956). The numbers of galaxies involved are so small that the difference
between the quoted percentages is not significant; an average figure of 15 ± 5 per cent
is therefore a fair estimate of the frequency of occurrence of observable λ 3727 emission

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lines. The observations on which this figure is based refer chiefly to isolated galaxies, members of small groups, and members of the Virgo cloud, while for ellipticals in dense clusters the frequency of occurrence is much smaller. In fact, of a total of twenty-five elliptical nebulae in four nearby clusters (Perseus, Coma, Hercules, Pegasus II), not a single one shows the \( \lambda 3727 \) emission line (Humason et al. 1956; the presence of \( \lambda 3727 \) is indicated by an asterisk on the spectral type in Tables I and II in their paper). The reason for the absence of observable \( \lambda 3727 \) lines among galaxies that are in clusters is that frequent collisions between cluster members sweep out the interstellar gas (Spitzer and Baade 1951).

Now those field nebulae which do have \( \lambda 3727 \) in emission exhibit a wide range in strength of the line, from very weak and barely detectable, as in NGC 5846, to quite strong and immediately apparent, as in NGC 4486 (Mayall 1956). It thus appears that there is a continuous range in the amount of ionized gas in these objects, and it therefore might also be imagined that there are some ellipticals containing still smaller amounts of ionized gas, too small to be detected with the available material, but not zero. A survey

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Observations of Elliptical Nebulae with Weak or Non-existent 3727 Emission Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nebula</td>
<td>Telescope</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 3377</td>
<td>200-inch</td>
</tr>
<tr>
<td>NGC 3585</td>
<td>200-inch</td>
</tr>
<tr>
<td>NGC 4125</td>
<td>200-inch</td>
</tr>
<tr>
<td>NGC 4472</td>
<td>100-inch</td>
</tr>
<tr>
<td>NGC 4649</td>
<td>100-inch</td>
</tr>
<tr>
<td>NGC 4697</td>
<td>100-inch</td>
</tr>
</tbody>
</table>

aimed at detecting very weak \( \lambda 3727 \) was therefore carried out as time permitted at Mount Wilson and Palomar Observatories, by taking spectrograms specifically for this purpose. The spectrograms were taken at a dispersion of about 190 Å/mm with either the 100-inch Newtonian-focus spectrograph or the 200-inch prime-focus spectrograph and were widened to about 0.9 mm by trailing the nucleus on the slit. The exposure time was long enough that the continuum near \( \lambda 3727 \) was well exposed, but not black, so that a weak emission line could be detected, and calibration plates were taken with auxiliary wedge or step-slit spectrographs, so that a line, if present, could be measured quantitatively for intensity. The exposure times are long, of the order of 4–6 hours with the 100-inch telescope for a nebula with \( m_{pg} = 10 \) in the system of Humason et al. (1956) and about 30 minutes for a similar nebula with the 200-inch telescope, but the plates are about optimum for detecting weak ultraviolet emission lines.

The results are collected in Table 1; of six nebulae observed, one proved to have \( \lambda 3727 \) in emission, while in the other five no emission line was detectable. In the ultraviolet spectral region the elliptical galaxies show a composite absorption-line spectrum dominated by K-giant features (Morgan and Mayall 1957), in which alternating blended absorption lines and relatively clear regions between them break up the spectrum and prevent the observation of weak emissions. Each nebular plate was traced on the microphotometer at the Astrophysics Laboratory of the California Institute of Technology, and the equivalent width and half-width of the \( \lambda 3727 \) emission line listed in Table 1
for NGC 4125 were derived from one of these tracings. On the other tracings an upper limit to the strength of a line that could escape detection was sketched, and the upper limits to the equivalent widths given in Table 1 were derived from these drawings (the equivalent widths are all in units of the local continuum near \( \lambda 3727 \), averaged over a band about 30 A wide). Fluctuations in the upper limit from plate to plate apparently depend chiefly on the definition of the nebular absorption-line spectrum, that is, on the dispersion in stellar velocities in the nucleus.

The large width of the observed emission line in NGC 4125, corresponding to a velocity spread of about 680 km/sec, is roughly similar to, but somewhat smaller than, the spread found in galaxies with very strong lines, as will be seen in the later sections of this paper. The number of nebulae observed is too small to draw any significant statistical conclusions, but the observation of the line in NGC 4125 shows that there certainly are some ellipticals with \( \lambda 3727 \) in emission too weak to be detected on existing radial-velocity spectral plates.

### III. \( \lambda 3727 \) EMISSION-LINE PROFILE IN NGC 4486

The E0 (Hubble) or kE1 (Morgan 1958) galaxy NGC 4486 is one of the three or four ellipticals with the strongest observed \( \lambda 3727 \) emission lines\(^1\) (Baade and Minkowski 1954; Mayall 1956). On plates of the nucleus taken with the 200-inch prime-focus spectrograph at a dispersion of 68 A/mm and a scale of 36.6/mm, the image of \( \lambda 3727 \) is very broad in the direction of the dispersion, indicating a large spread in internal velocity but the image is quite narrow in the direction normal to the dispersion (only 1" on an hour exposure), indicating an emitting region small in angular extent. The bright \( \lambda 3727 \) emission is confined to the nucleus and does not extend into the so-called jet, which has a relatively blue continuous spectrum presumably due to synchrotron radiation (Baade and Minkowski 1954; Baade 1956; Shklovsky 1957).

In order to study the velocity dispersion of the interstellar gas in the nucleus, a spectrogram widened to 0.9 mm was taken with the 100-inch spectrograph, in just the same way that the spectral plates described in Section II were taken, and the line profile was measured on this spectrogram. The result is presented graphically in Figure 1, where it may be seen that the profile is strikingly asymmetrical and might even be called double, as was first noticed by Minkowski (private communication; see Minkowski 1959). The two “components” of this \( \lambda 3727 \) emission line differ in central wave length by approximately 11 A or 900 km/sec, and the stronger component has approximately the same velocity as the stellar absorption lines, so that the mean velocity of the blended feature is several hundred kilometers per second smaller than the absorption-line velocity (Minkowski 1959). The origin of this peculiar profile is quite uncertain, but it appears to be unique to NGC 4486 and possibly to be causally associated with its strong non-thermal radio emission.

### IV. EXTENT AND ROTATION OF THE EMITTING REGION IN NGC 4278

NGC 4278 is a nearly round elliptical galaxy, type E1 in the system of Hubble (Humason \textit{et al.} 1956), kE1 in the system of Morgan (1958). It is fairly bright, apparently moderately close to our Galaxy, and in a convenient part of the sky, and it has a strong \( \lambda 3727 \) emission line; hence it was selected for further detailed study of the interstellar gas in an otherwise representative elliptical nebula.

In an effort to map the distribution of emitting gas in this system, several long-exposure spectrograms were taken with the prime-focus spectrograph of the 200-inch telescope at a dispersion of 68 A/mm near \( \lambda 3727 \). These exposures were taken with the

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\(^1\) I am most grateful to Dr. M. L. Humason, who allowed me to use freely his entire collection of spectrograms to estimate emission-line strengths. My program would have been impossible to carry out without his generous help.
nucleus of the galaxy held fixed on the center of the slit (by guiding with an auxiliary microscope on a guide star, just as in direct photography), so that they provide a one-dimensional image of the spatial distribution of excited O+. Several exposures were taken (on different nights; the individual exposure times are of the order of 5 hours each) with the slit in various position angles, chosen with reference to the position angle 18°, the position angle of the major axis of the nebula as seen on long-exposure 48-inch Schmidt plates. In this connection it may be noted that not only NGC 4278 but also nearly all giant elliptical galaxies with zero or small ellipticity appear more elongated on the 48-inch Schmidt plates, which show their faint outer regions, than on Hubble’s 100-inch plates, which generally show the somewhat brighter regions closer to the centers of the nebulae.

![Graph of [OII] λ3727 profile](image)

**Fig. 1.**—Measured emission-line profile of λ 3727 in the nucleus of NGC 4486

On all three spectrograms the image of the λ 3727 doublet is inclined, indicating rotation, and is also highly broadened at the position corresponding to the center of the nucleus, indicating large turbulent velocities. On the longest exposures (4–5 hours) the measured widths at the center of the nucleus correspond to a spread in velocity of 890 km/sec, while on shorter exposures (1 hour) the spread is 630 km/sec. The range in velocity decreases rapidly with increasing distance from the center of the nucleus, so that the emission line has an approximately quadrilateral shape, two tips corresponding to the largest distance from the center but almost zero spread in velocity, the other two corners to the maximum positive and negative velocities exactly at the center. The λ 3727 emission is brightest at the center of the nucleus and drops off rapidly with distance. On a pair of short-exposure spectrograms, each 1 hour long, taken in immediate succession on the same night, the extent of the λ 3727 image is 2'6 along the major axis and 3'4 along the minor axis, while on a pair of longer exposures taken on successive nights the extent of the image is 3'9 along the major axis (5.7 hours’ exposure) and 4'5 along the minor axis (4.3 hours’ exposure, ended by clouds). These measures are difficult to make, but they indicate that the interstellar gas in the nucleus apparently has a slightly elliptical distribution with the long axis perpendicular to the long axis of the
outer part of the galaxy, as seen in the continuous radiation of the stars. It is, at any rate, certain that the gas does not form a much more highly flattened system than the stars, even though the velocity measurements show that there is a significant rotational-velocity component in the line of sight.

At the outer ends of the $\lambda$ 3727 images on the longest exposures, the turbulent velocity is nearly zero, and it appears that, still farther out on the major-axis spectrogram, very weak, completely resolved $\lambda$ 3726 and $\lambda$ 3729 lines can be seen, the latter being the stronger. These lines have a smaller slope than the $\lambda$ 3727 blend in the nucleus, indicating a smaller angular velocity, and are essentially not broadened at all. The fact that they can be seen on the exposure taken with the slit along the major axis but not on the perpendicular exposure suggests that they originate in a rotating, non-turbulent, flattened system of interstellar gas, of the type studied by Spitzer (1942). This point is not certain, however, because the resolved lines in the outer part of the galaxy are quite weak and because the minor-axis spectrogram is not exposed quite so heavily as the major-axis plate. In an effort to map the $\lambda$ 3727 emission still farther out in the nebula, a pair of long-exposure plates was taken at lower dispersion (approximately 380 A/mm) with the 100-inch Newtonian-focus spectrograph, using a very fast camera ($F/0.67$ solid-block Schmidt). However, at this dispersion the Herzberg $O_2$ bands of the night airglow (Chamberlain 1955) blend with the red-shifted $\lambda$ 3727 doublet, which therefore cannot be measured outside the nucleus on these spectrograms. An optical device combining great speed and high wave-length resolution will be necessary for further study of the emission in the outer regions of the galaxy.

If we adopt 4.2" as the mean angular diameter of the region in which bright $\lambda$ 3727 emission is observed, we can compute the linear size of this emitting region from the distance of the nebula. Although many globular clusters are visible on the 200-inch photographs of this galaxy, no photometric measurements of them are available as they are in NGC 4486 (Baum 1955), and the distance can be found only from the red shift. The measured velocity, corrected for solar motion, is $+615$ km/sec (Humason et al. 1956), which, with an adopted Hubble constant of approximately 75 km/sec/10$^6$ pc (Sandage 1958), corresponds to a distance of $8.2 \times 10^6$ pc or a distance modulus $m - M = 29.6$. The distance of an individual nearby object derived in this way from its velocity is highly uncertain, because the random motions of field galaxies are of the order of 200–300 km/sec (Humason et al. 1955), but no better estimate of the distance is available. The absolute photographic magnitude of NGC 4278, on the system defined by Humason et al. (1956), then, is $-18.4$, about 2.5 mag. fainter than the brightest Virgo-cluster ellipticals, but much brighter than the dwarf object N32, which has absolute magnitude $M_B = -15$ on a somewhat similar photometric system (de Vaucouleurs 1958). The calculated diameter of the bright nuclear region in which $\lambda$ 3727 is emitted, then, is $1.7 \times 10^8$ pc, larger than a typical $H\pi$ region in our own Galaxy but not by an order of magnitude.

The slope of the rotationally inclined $\lambda$ 3727 emission line on the three long-exposure spectrograms was measured by means of a projection-type machine at the Yerkes Observatory, designed originally for double-star work. The results, expressed as velocity gradients in angular units, are listed in Table 2; the lines are straight to within the measurement errors, indicating uniform angular velocity within the emitting region. The measured gradients can be analyzed simply, to find the component of angular velocity projected on the plane of the sky, as well as its position angle (Burbidge, Burbidge, and Prendergast 1959a). The result is that the component on the plane of sky is about 52 km/sec/second of arc in position angle 119°, so that the major axis of the galaxy, if it were flattened by rotation in the same direction, should lie in position angle 29°. The discrepancy between this position angle and the value 18° given above cannot be regarded as significant, because the deviation of the shape of the galaxy from a circle is so small that the direct visual estimate is rather poor.
The projected angular velocity, 52 km/sec/second of arc, becomes 1.3 km/sec/pc at the distance 8.2 \times 10^6 pc, and the whole range in velocity from one side to the other of the emitting region is 220 km/sec. The uncertainty in the velocity gradient is probably of the order of \pm 15 km/sec/second of arc, and any component of angular velocity there might be in the line of sight cannot be measured by the Doppler effect.

V. EMISSION-LINE PROFILES IN NGC 4278

Although the spectrograms discussed above show the interstellar emission lines, they are too narrow in the direction perpendicular to the dispersion for quantitative study. A series of widened spectrograms of NGC 4278 was therefore obtained, together with photometric calibration plates, taken with the linear-wedge spectograph at Palomar Observatory and processed with the nebular exposures. These spectrograms were broadened to 0.9 mm by trailing the nucleus on the slit, and they therefore record not only the light originating in the nucleus but also some contribution from the fainter parts of the galaxy outside the center. This background contribution is relatively minor, however, as shown by the surface photometry discussed in the next section, and we shall therefore treat the spectrograms as if all the light originated in the nuclear emission region with its diameter of 4.2''.

<table>
<thead>
<tr>
<th>Plate</th>
<th>Position Angle of Slit</th>
<th>Measured Gradient (km/sec/sec of arc)</th>
<th>Computed Gradient (km/sec/sec of arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-679</td>
<td>18°</td>
<td>54</td>
<td>51</td>
</tr>
<tr>
<td>N-486</td>
<td>90°</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>N-680</td>
<td>108°</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

The \( \lambda 3727 \) emission line is so strong that an exposure long enough to record the continuum shows the center of the line completely black, and therefore several spectrograms were taken with different exposure times and combined to give the entire profile. These plates were taken at a dispersion of 192 Å/mm, which is sufficiently high for the broad lines in this galaxy, and they show not only the \( \lambda 3727 \) emission line but the \( [\text{Ne} \text{ III}] \) \( \lambda 3869 \) line as well. Other spectrograms were taken of the blue-green spectral region, at a dispersion of 184 Å/mm, and of the red spectral region, at a dispersion of 177 Å/mm, all with the same slit width and all widened in the same way to 0.9 mm; the emission lines listed in Table 3 were measured on these plates. The spectrograms, with their individual calibration plates, were traced on the microphotometer at the Robinson Astrophysics Laboratory of the California Institute of Technology and were reduced to intensities. The unit of intensity for each line was the average intensity of the local continuum, and the individually measured profiles were averaged or combined to form a mean profile for each line (the number of spectrograms used for each profile is given in the last column of Table 3).

The \( \lambda 3727 \) line, being much brighter than the local continuum, is very well determined and is shown graphically in Figure 2, where it can be seen that the broadening by internal motions is so great that there is no sign of the separation of the two fine-structure components, which are 2.75 Å or 220 km/sec apart. The other lines are weaker, in units of the local continuum, and therefore are correspondingly less well determined; two examples of such profiles are shown in Figure 3. In Table 3 the measured equivalent
widths of all the observed emission lines are listed, together with the full widths (expressed in velocity units) of the profiles to their half-intensity points; the widths are all essentially the same and are probably best represented by 624 km/sec, the value determined from \( \lambda 3727 \). The hydrogen emission lines are special cases, because their absorption lines are also present and therefore the measured emission-line strength is fictitiously too small. To correct for this effect, two spectrograms each of the Ha and H\( \beta \) regions were taken with the same spectrograph of another elliptical galaxy, NGC 3379, a nearly round system (E0 or kE1) (Humason et al. 1956; Morgan 1958) without interstellar

**Table 3**

**Interstellar Emission Lines in Nucleus of NGC 4278**

<table>
<thead>
<tr>
<th>Wave Length (Å)</th>
<th>Ion</th>
<th>Equivalent Width (Å)</th>
<th>Width (km/sec)</th>
<th>Relative Intensity</th>
<th>No. of Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>3727</td>
<td>[O II]</td>
<td>50.8</td>
<td>624</td>
<td>14.5</td>
<td>5</td>
</tr>
<tr>
<td>3869</td>
<td>[Ne III]</td>
<td>3.6</td>
<td>640</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>4961</td>
<td>H( \beta )</td>
<td>2.3*</td>
<td>725</td>
<td>5.0</td>
<td>2</td>
</tr>
<tr>
<td>5007</td>
<td>[O III]</td>
<td>3.8</td>
<td>671</td>
<td>3.8</td>
<td>2</td>
</tr>
<tr>
<td>6548</td>
<td>[N II]</td>
<td>1.7</td>
<td>545</td>
<td>1.7</td>
<td>3</td>
</tr>
<tr>
<td>6563</td>
<td>Ha</td>
<td>3.8†</td>
<td>613</td>
<td>6.4</td>
<td>3</td>
</tr>
<tr>
<td>6583</td>
<td>[N II]</td>
<td>5.5</td>
<td>604</td>
<td>5.5</td>
<td>3</td>
</tr>
</tbody>
</table>

* H\( \beta \) equivalent width corrected for underlying absorption line: 5.0 Å.
† Ha equivalent width corrected for underlying absorption line: 6.4 Å.

**Fig. 2.—**Measured emission-line profile of \( \lambda 3727 \) in the nucleus of NGC 4278
emission lines. The measured absorption-line profiles in this galaxy have equivalent widths of 2.7 Å (Hβ) and 2.6 Å (Ha), and these widths were added directly to the measured emission-line widths in NGC 4278, to find the corrected equivalent widths given in the footnotes to Table 3 and used in the remainder of the discussion. The uncorrected emission-line profile of Ha measured in NGC 4278 and the absorption-line profile measured in NGC 3379 are shown in Figure 4.

The measured equivalent widths of the emission lines can now be converted to relative intensities, using the spectral-energy distribution of the underlying nebular continuum. It is known from multicolor-photometry results (Tifft 1958) that the continuous spectrum of NGC 4278 is quite similar to the continuous spectra of all other nearly giant E and S0 galaxies and therefore, in particular, to the spectrum of the well-observed object NGC 4374. The energy-curve of this galaxy, determined with a photoelectric scanning spectrograph (Code 1959), has therefore been used in the reduction, and the resulting relative emission-line intensities are listed in Table 3. These relative intensities are roughly similar to those observed in a galactic diffuse nebula, such as NGC 1976, the

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![Figure 3](image1.png)

**Fig. 3.**—Measured emission-line profiles of λ 5007 and λ 6583 in the nucleus of NGC 4278

![Figure 4](image2.png)

**Fig. 4.**—Measured emission-line profile of λ 6563 in NGC 4278; measured absorption-line profile of same line in NGC 3379.
Orion Nebula (Aller and Liller 1959), or to the intensities in a very low-excitation planetary nebula, such as IC 418 (Aller 1941).

The relative abundances can now be converted into relative abundances of the ions involved, and this has been done by using for the hydrogen lines the theory worked out for Case B (complete self-absorption of Lyman line radiation) by Burgess (1958) and for the forbidden lines of the heavy elements the collision cross-sections tabulated by Seaton (1959). The two observed hydrogen lines differ between themselves, since the observed ratio of strengths is $H\alpha/H\beta = 1.3$, while the expected ratio according to the calculations is $H\alpha/H\beta = 2.6$, and, according to observations of diffuse nebulae in our Galaxy, possibly even greater (Pottasch 1960). These two emission lines are the most difficult of the nebular lines to measure accurately because of the underlying absorption lines previously discussed, and the observational result for hydrogen must be considered as uncertain by a factor of 2. The forbidden lines can be measured more accurately, because there are no corresponding absorption lines, and, indeed, the observed ratio of strengths of the two [N II] lines $\lambda 6583/\lambda 6548 = 3.2$ agrees satisfactorily with the computed ratio 3.0, which depends only on the ratio of transition probabilities (Garstang 1951). However, in the reduction of intensities to abundances, the kinetic (or electron)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Assumed Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10000°</td>
</tr>
<tr>
<td>H+</td>
<td>$1.0 \times 10^4$</td>
</tr>
<tr>
<td>N+</td>
<td>0.34</td>
</tr>
<tr>
<td>O+</td>
<td>1.54</td>
</tr>
<tr>
<td>O++</td>
<td>0.49</td>
</tr>
<tr>
<td>Ne++</td>
<td>0.33</td>
</tr>
</tbody>
</table>

temperature enters as an unknown parameter, and the calculations have been made for two assumed values, $T = 10000°$, approximately the temperature of nearby diffuse nebulae in our Galaxy, and also $T = 20000°$, a temperature that some planetary nebulae reach. The results, listed in Table 4, give the relative abundances of the ions responsible for the observed lines. The most directly physically significant quantities are the relative abundances of the nuclei, and these can be derived for the ratio of hydrogen to oxygen, since, if hydrogen is ionized, oxygen is also (because of their near-equality in ionization potentials) and because the observed low-excitation spectrum suggests that there is little, if any, O+++ and higher stages of ionization. The results are $H/O = 4.9 \times 10^4$ at an assumed temperature 10000°, or $H/O = 4.0 \times 10^4$ at an assumed temperature of 20000°; for comparison, a figure often quoted for the normal value of this abundance is $H/O = 1.9 \times 10^8$ from the compilation of Aller (1953). Thus either the interstellar matter in NGC 4278 is approximately similar to the interstellar matter in our Galaxy in relative abundance of heavy elements and also in temperature, or else the interstellar matter in NGC 4278 has an abnormally low heavy-element abundance and a correspondingly abnormally high temperature. That both these situations are possible is a consequence of the fact that the cooling of ionized interstellar gas occurs mostly by forbidden-line radiation, so that a decrease in heavy-element abundance is compensated for by an increase in temperature, leaving the average level of line emission unchanged. The temperature and relative abundance can, in principle, be found separately by measuring
temperature-sensitive line ratios, such as [O III] λ 5007/λ 4363, but λ 4363 and all other suitable lines are too weak to be observed in the present case. Thus the problem of the relative elemental abundances in the interstellar gas in elliptical nebulae remains unsolved.

The widths of the line profiles, listed in Table 3, and the appearance of the spectral lines, described in Section IV, suggest that the gas in the nucleus is strongly turbulent. As we have pointed out in a previous paper (Minkowski and Osterbrock 1959), this random motion would be expected to be damped out very rapidly (in a time of the order of the dimension of the system divided by a characteristic velocity, say 10^6 years), and its presence shows that energy is somehow fed rapidly into the interstellar gas. It is likely that the energy source is ultimately the kinetic energy of stellar motion, but just how it is transferred to the gas, either gravitationally or radiatively, is not known.

If it is assumed that only gravitational forces are effective in causing motions of the interstellar gas, it is possible to estimate the total mass in the nucleus (presumably mostly stars) from the observed velocities. In the conventional application of this scheme to spiral galaxies, the rotational velocities are analyzed, to give the mass (see, e.g., Schmidt 1957), and the correction for superimposed random motions small in comparison with the rotational motions has been given by Oort (1940). However, in NGC 4278 the random motions are large in comparison with the rotational motions, and a different analysis is necessary, as Dr. K. H. Prendergast first pointed out to me (see Poveda 1958; Burbidge, Burbidge and Prendergast 1959). The general theory with both rotation and turbulence has apparently not been worked out, but an approximate value for the mass can be found by neglecting the rotational velocity (which varies by 220 km/sec across the nucleus) in comparison with the random velocity (which ranges over about 625 km/sec to half-intensity). On this hypothesis the gas distribution is completely spherical and is supported against gravitation only by its random motions, and so the equation of hydrostatic equilibrium may be written

\[ \frac{-GM_r \rho}{r^2} = \frac{dP}{dr} = \frac{d}{dr} \left( \rho \langle v^2 \rangle \right), \]

where \( M_r \) is the total mass within a radius \( r \), \( \rho \) is the density of interstellar gas, and \( \langle v^2 \rangle \) is its mean-square radial velocity. Then in order of magnitude we may approximate \( M_r \) and \( r \) by \( M \) and \( R \), the mass and radius of the nucleus, and take the derivative to be \( \langle v^2 \rangle /R \), where \( \langle v^2 \rangle \) now is a representative mean-square velocity in the nucleus, so that, finally,

\[ M = \frac{R \langle v^2 \rangle}{G}. \]

We take \( R = 85 \) pc and \( \langle v^2 \rangle = (400 \text{ km/sec})^2 \) as rough estimates from the measures discussed above, and find \( M = 3 \times 10^9 \) solar masses in the nucleus, or a mean density of \( 1.2 \times 10^3 \) solar masses/pc^3 in the nucleus. The main uncertainty in this figure arises not from the approximations made in the derivation but rather from the uncertainty in the initial hypothesis that only gravitational forces are significant.

VI. SURFACE PHOTOMETRY

Since the spectroscopic observations of the λ 3727 emission line in NGC 4278 all refer to the bright central nucleus, about 4'' in diameter, it is of some interest to find the intensity in the continuous spectrum of this same region. This information is necessary both to reduce the spectroscopic data to energy units and also to interpret the observations in terms of relative amounts of gas and stars. Though considerable work has been done on the luminosity distribution in elliptical galaxies (see de Vaucouleurs 1959 and references given there), there are no published results on NGC 4278 close enough to its
The observations were made photographically, with the 100-inch reflector, using 103a-D plates and a Schott GG11 filter, so that the color system is very similar to the photovisual or Johnson and Morgan V system (Sandage 1953). The main problem in this type of surface photometry is that good angular resolution is required, while the nucleus is bright and there is no difficulty caused by limited available light. Therefore, all the direct exposures were taken several hours after dark on a night of nearly uniform temperature, so that the 100-inch telescope was in thermal equilibrium and had a good figure (Baade 1944); in addition, the telescope was stopped down to 58-inch diameter to reduce further any residual spherical aberration or astigmatism (Arp, Baum, and Sandage 1953). No single exposure can cover the wide range of intensities that occur near the center of an elliptical galaxy, and therefore a series of eight plates ranging from 20 seconds to 27 minutes in exposure time was obtained. Several calibration plates, covering the same range in exposure time, were taken with the linear-wedge spectrograph in the 100-inch dome and were developed along with the direct exposures.

All the direct plates (except the shortest and longest exposures) were traced on the microphotometer at the Yerkes Observatory, along with the calibration spectrograms (which were traced at the wave length \(\lambda 5700\) A). Each image of the galaxy was traced along two perpendicular lines passing through its center; one of these lines also passed through the center of the image of a faint star 10'6 north of the nucleus, which thus served to define this direction. The analyzing slit on the microphotometer was adjusted to a square shape, small enough that the image of the star as it appeared on the Brown-recorder tracing was about 1'4 in diameter. Each tracing was reduced to intensities through the use of the calibration-curve derived from a wedge spectrogram of approximately the same exposure time, and the results, in the form of log intensity versus distance from the center, were plotted separately for each tracing. Each of the plots has an image of the galaxy with an overexposed central region and an underexposed outer region bracketing a correctly exposed range in which accurate photometry can be carried out; the distance of the well-exposed region from the center depends on the exposure time of the plate. The measurements made on different exposures were combined by sliding the logarithmic plots up and down, keeping the distance-from-the-center scales in register, until the well-exposed ranges on each tracing fitted smoothly onto one another (there is good overlapping of these regions from one exposure to the next). This procedure amounts to preserving the intensity scale on each exposure separately and building up the over-all large range in intensity by fitting the ends of the separate sections together. The surface brightness-curve found in this way, covering a range of intensity over a factor of approximately 50 within a distance of 20" from the center of the nebula, is shown in Figure 5; the unit of intensity in this curve remains arbitrary. It can be seen that the measured central intensity differs slightly by 0.07 in the logarithm on the two perpendicular directions; this is a measure of the photometric inaccuracies of the method. The two curves are nearly, but not quite, similar, indicating that the isophotes are nearly round within 20" of the center in this elliptical galaxy.

The photometric results described above can now be transformed into magnitudes on the V system (Johnson and Morgan 1953) by the use of photoelectric measurements made by Tifft (1958). His observations were made with various color filters, two of which (Nos. 3 and 4) average to a wave length fairly similar to the F-filter representative wave length, and were made through circular diaphragms of various sizes centered on the galaxies. For NGC 4278, the smallest diaphragm had a radius of 18", within which the measured magnitude was \(V = 11.3\), and we can therefore find the integrated brightness within this radius from the curves given in Figure 5 and thus fix the unit of intensity. This has been done, using an average of the four radial surface brightness-curves measured (two in each direction, one on each side of the center) and assuming radial
symmetry, with the result that the total light within 18'' radius is 9.71 \times 10^2 intensity units/square second of arc, so that one intensity unit corresponds to one 18.7-mag. star per square second of arc.

The apparent magnitude of the nucleus, that is, the part of the galaxy within 2'' radius, can now be found from the same integration, and the result is \( V = 13.1 \) mag. With the distance modulus of \( m - M = 29.6 \) adopted in Section IV, the absolute magnitude of the nucleus (within 80-pc radius) is thus \( M_{\nu} = -16.5 \). Hence the nucleus is 21.3 mag. brighter than the sun in visual absolute magnitude (Stebbins and Kron 1957) or \( 3.32 \times 10^8 \) brighter in visual luminosity. If we adopt \( F_\lambda = 8.62 \times 10^6 \text{ ergs/cm}^2 \text{ sec } \lambda \) as the flux from the sun at the representative visual wave length \( \lambda 5540 \) (Minnaert 1953), the luminosity of the nucleus at this same wave length is thus \( L_\lambda = 1.74 \times 10^{38} \text{ ergs/sec} \).

![Intensity profile in central region of NGC 4278](image)

**Fig. 5.**—Intensity profile in central region of NGC 4278. *Left curve,* along a line from north (+) to south (−); *right curve,* along a line from east (+) to west (−). Unit of intensity: one star with \( V = 18.7 \) per square second of arc.

sec \( \lambda \). Using the average spectral-energy distribution for elliptical galaxies found by Code (1959) and described in Section V, the luminosity of the nucleus at H\( \beta \) is the same as the luminosity at \( \lambda 5540 \), and if the equivalent width of the H\( \beta \) emission is taken to be 3.8 \( \text{A} \) (the average of the direct H\( \beta \) determination, 5.0 \( \text{A} \), with the value computed from the Ha equivalent width and the theory of Burgess 1958, 2.6 \( \text{A} \)), we finally find the luminosity in the H\( \beta \) emission line to be \( L_\beta = 6.6 \times 10^{38} \text{ erg/sec} \).

This measured luminosity in a hydrogen emission line can now be used to estimate the amount of ionized interstellar gas in the nucleus of NGC 4278, for the amount of energy radiated in the line depends on the temperature, density, and volume, that is, on the physical conditions and the amount of gas. Table 5 presents values, computed according to the theory of Burgess (1958), of the effective radius of the emitting volume (defined by \( r = 4 \pi R^3 / 3 \)) and also values of the total mass of ionized hydrogen, for various assumed electron densities and temperatures (an estimated helium abundance of 10 per cent by mass with respect to hydrogen has been adopted). It can be seen that densities lower than 10 electrons/cc are ruled out by the fact that the effective radius of the ionized volume cannot exceed 80 pc, the radius of the nucleus itself; on the other
and, densities higher than, say, 300 electrons/cc are ruled out in NGC 1052 by the measured $\lambda$ 3727 wave length (Minkowski and Osterbrock 1959) and hence in all likelihood do not occur in NGC 4278 either. We therefore conclude that the mean density of ionized gas in the nucleus of NGC 4278 is in the range 10–300 electrons/cc, and the mass of this gas is in the range $10^4$–$10^6$ solar masses.

If we combine the visual luminosity of the nucleus found above, namely, $3.3 \times 10^8 L_\odot$, with the mass of the nucleus tentatively estimated in the previous section, namely, $3 \times 10^9 M_\odot$, we find the ratio to be about $M/L = 9 M_\odot/L_\odot$, a value relatively low in comparison with estimates of this ratio for other ellipticals in double-galaxy systems or clusters of galaxies (see Limber 1960).

The mass of interstellar gas deduced above (at most, $10^6$ solar masses) is small in comparison with the estimated total mass of the nucleus, around $3 \times 10^9 M_\odot$. This small fraction of mass could easily have been lost by evolving stars in the course of their history or, alternatively, could have been interstellar matter that had never been part of a star since an early epoch (Minkowski and Osterbrock 1959).

TABLE 5

<table>
<thead>
<tr>
<th>TABLE 5</th>
<th>EFFECTIVE RADIUS AND MASS OF IONIZED INTERSTELLAR GAS IN NUCLEUS OF NGC 4278 FOR VARIOUS ASSUMED ELECTRON DENSITIES AND TEMPERATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_e$ (cm$^{-3}$)</td>
<td>$T = 10000^\circ$</td>
</tr>
<tr>
<td>R (pc)</td>
<td>$M$ (M$\odot$)</td>
</tr>
<tr>
<td>1</td>
<td>360</td>
</tr>
<tr>
<td>10</td>
<td>78</td>
</tr>
<tr>
<td>$10^2$</td>
<td>17</td>
</tr>
<tr>
<td>$10^3$</td>
<td>4</td>
</tr>
</tbody>
</table>

Finally, from the measured surface brightness-curve, we can estimate the contribution to the trailed spectrograms made by light originating outside the nucleus. The length of the slit is 3 mm, projecting into about $34''$ on the sky, and we find by integration that if all the light falling on the photographic plate had equal effect, then almost exactly 50 per cent of the blackening would arise from light originating in the nucleus (within $4''$ diameter). Because of reciprocity-law failure, which tends to weaken the effect of light from the faint outer regions of the galaxy, the nucleus actually contributes somewhat more than half the total photographic effect, and it is therefore reasonable (in the absence of any quantitative information on the line strength in the outer part of the nebula) to treat the spectrograms as if they referred entirely to the nucleus.

VII. DISCUSSION

The observations presented above show that the mass of interstellar gas in the nucleus of the elliptical galaxy NGC 4278 is similar in many ways to an exceptionally large gas cloud in our Galaxy. The emission-line spectrum of NGC 4278 is comparable to the spectrum of an H$\alpha$ region and is consistent with "normal" relative abundances of the elements and temperature, though somewhat lower heavy-element abundances, together with a somewhat higher temperature, are also possible. The size of the gas cloud in the nucleus, roughly 170 pc in diameter, is large in comparison with a typical galactic H$\alpha$ region but is comparable with, or only slightly larger than, some of the largest aggregates with diameters of the order of 100 pc.
There are differences also, however, between the gas in the nucleus of the elliptical and the gas in a typical gas cloud in our Galaxy. First of all, the interstellar gas in the elliptical has a very large random velocity dispersion, and, second, the ionization is almost certainly not due to ultraviolet radiation from normal O stars. These two differences may be causally related; that is, the high velocity dispersion may dissipate sufficient energy to keep the gas ionized, though this interpretation is by no means certain. The turbulence would decay rapidly unless energy were supplied to it at the same rate that it was dissipated, and this energy probably would come ultimately from the kinetic energy of the stars. However, the energy transfer by gravitational forces between stars and interstellar gas at relative velocities of hundreds of kilometers/sec is not at all effective (Spitzer and Schwarzschild 1951; Osterbrock 1952), and it is likely that the transfer occurs instead by ultraviolet radiation (Oort and Spitzer 1955). If there are faint hot stars in the elliptical similar to the faint hot stars in globular clusters, these stars could transfer kinetic energy to the gas through their ionizing radiation. They would also supply ionization energy at the same time, and, in fact, so little is required that the M3 population with its few hot blue stars, if scaled up in number to give the visual luminosity of the nucleus of NGC 4278, would also give more than enough ionizing radiation (Minkowski and Osterbrock 1959). Thus either the decay of turbulence or ultraviolet radiation from hot stars is a possible source of energy for the observed emission-line spectrum of the interstellar gas in NGC 4278. The longest exposures appear to show λ 3727 in emission in the outer non-turbulent part of the galaxy, and if this suggestion could be verified, it would be evidence in favor of radiative excitation of at least part of the gas.

A remote possibility is that weak ultraviolet radiation from the very numerous cool stars in the elliptical population provides some of the source of ionization of the gas. The formulae of Strömgren (1939) show that if the stars radiated in the ultraviolet (short of 912 Å) at the same rate as black bodies, say, at the sun's effective temperature, 5730° K, the radiation would be insufficient by a very large factor, about 10⁷, to explain the observed ionization. In the near ultraviolet region (1000–2000 Å) the sun's radiation is considerably less than the radiation from a 5730° K black body, while the solar radiation just short of 912 Å has not been quantitatively measured (see Friedman 1959). However, in the X-ray region between 15 and 150 Å, the sun radiates, apparently largely in the form of emission lines, roughly the same amount of energy as a 5730° K black body radiates in its continuous spectrum at all wave lengths short of 912 Å, and this X-ray radiation, which probably arises in the upper chromosphere and inner corona, varies strongly with solar activity (see Friedman 1959). Thus it is conceivable that some late-type stars might have sufficiently hot or extensive outer layers to produce much more short-wave-length radiation than the sun does and that if these stars occurred in large numbers in an elliptical galaxy, they would be responsible for some of the ionization of the gas in that elliptical. This suggestion is completely uncheckable at present and thus is only an interesting possibility.

The observed mass of ionized gas in the nucleus of the elliptical is so small that it is quite possible that there is a larger fraction of neutral gas present also. Indeed, one might easily assume that all ellipticals contain neutral gas and that those galaxies with λ3727 in emission are objects in which some of the gas is ionized. Efforts to detect neutral gas through the 21-cm emission line are so far not decisive, since both positive (Heeschen 1957) and negative (Raimond and Volders 1957) results have been reported in the nearest and brightest elliptical, M32. When larger radio telescopes come into use, it will be possible to study some of the giant ellipticals similar to NGC 1052 and NGC 4278, to find whether or not neutral hydrogen is present and, if it is, even to find the amount of gas and its velocity dispersion as a function of galactic type, amount of ionized gas, etc.

The center of our own Galaxy is not directly observable optically because of the heavy interstellar extinction, but the radio source Sagittarius A is probably a mass of ionized
gas at the galactic center, perhaps similar to the mass of ionized gas in the elliptical NGC 4278 (Oort, Kerr, and Westerhout 1958). The source is complicated, being made up of one or more thermal sources (large H II regions) with a total mass of order $10^6 M_\odot$ within a diameter of 40 pc or so, as well as some surrounding non-thermal sources (Drake 1959). Therefore, the mass and density of ionized gas near the center of our Galaxy are comparable with the mass and density near the center of NGC 4278. The velocity distribution of the gas in the nucleus of our Galaxy cannot be determined from the radio-continuum measurements, but 21-cm observations show that the neutral hydrogen has quite high velocities (Oort and Rougoor 1960), which suggests that the ionized gas probably also has a high velocity dispersion. Thus the explanations that have been suggested for the space and velocity patterns in the nucleus of our Galaxy, involving flow of gas possibly from a high-temperature galactic corona and possibly in a magnetic field (Drake 1959; Oort and Rougoor 1960), may also apply in the elliptical galaxy. It must be noted, however, that optical spectrograms of the nearby spirals M31 (Münch 1960) and M81 (Münch 1959) show that in both these objects the ionized gas close to the nucleus has a low velocity dispersion. If the nucleus of our Galaxy is similar to these nuclei, it would mean that the velocities measured in the neutral hydrogen are quite different from the velocities in the ionized gas and that the analogy between the nucleus of our Galaxy and the nucleus of NGC 4278 is incorrect.

The mass of stars within the nucleus is of the order of $3 \times 10^9 M_\odot$, if the somewhat questionable assumption that only gravitational forces need to be considered in calculating the motion of the gas is true. This mass leads to a mass-to-light ratio of approximately $10 M_\odot/L_\odot$ in the nucleus, a value somewhat lower than the generally quoted ratio for ellipticals, of order 30–100 (Limber 1960), but higher than the ratio 3.3 estimated for M32 by Poveda (1958).

The final conclusion is that, though the gas in the center of elliptical galaxies can be described from the observational data given above, the ultimate causes for these observed properties are not known. Surveys for $\lambda 3727$ in the nuclei of a larger sample of elliptical galaxies would appear to be a promising line for continuing the study of this problem, together with surveys with large radio telescopes for neutral hydrogen. Measurements of the strength of $\lambda 3727$ in the outer part of ellipticals would also be very informative.

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