ULTRAVIOLET EMISSION FROM GALAXIES

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ABSTRACT

The ultraviolet radiation from normal elliptical, spiral, and irregular galaxies and from abnormal objects (radio sources, quasi-stellar objects, and Seyfert galaxies) is discussed. A list of expected emission lines is compiled from previously published lists for planetary nebulae. The problem of the passage of Lyman α radiation from the source to the observer is reviewed and possible Lyman α fluxes from various types of normal and abnormal galaxies are estimated for the case that most of the Lyman α generated in the source can escape from it. The abnormal galaxies should be the stronger Lyman α emitters. Finally, it is shown that quasi-stellar radio sources in the apparent visual magnitude range 17-19 can have redshifts in the range z = 1-2, and Lyman α can come into the wavelength region accessible from the ground. To facilitate line identifications in existing spectra of such objects, ultraviolet spectra of planetary nebulae and of the relatively bright object 3C273 are greatly needed.

I. INTRODUCTION

The possibility of observing the ultraviolet radiation from galaxies is of interest from two points of view. Firstly, we would like to know whether such observations, either of line or continuum radiation, can give new information on the physical conditions in external galaxies. Secondly, if there is a particularly strong emission line in the ultraviolet (and the possibility that hydrogen Lyman α might be such a line springs to mind at once), this could be important for redshift measurements, particularly in dealing with very distant galaxies with large redshifts. Thus ultraviolet observations may be important for the cosmological problem.

We may divide external galaxies into two broad classes - normal galaxies (ellipticals, spirals, and irregulars), and the galaxies that are abnormal in the sense that a violent release of energy appears to have taken place in them recently (Burbidge, Burbidge, and Sandage 1963). The strong radio emitters fall into the latter category, including both objects like Cygnus A, and also the even more puzzling quasi-stellar radio sources. Greenstein and Schmidt (1964) have shown that the quasi-stellar objects must lie outside our own Galaxy, and present knowledge suggests that they are very distant abnormal galaxies putting forth up to 100 times as much light in the optical region as the brightest normal galaxies. In the radio region, however, they are no stronger than the strongest of the radio galaxies like Cygnus A. The very large energy releases which are necessary to account for the radio radiation have been a topic of considerable discussion during the last few years (see, for example, Burbidge and Burbidge 1965). The physical conditions in the quasi-stellar objects are obviously of very great interest, and studies of the ultraviolet radiation from them will be of great importance. In the category of abnormal galaxies we shall also include the Seyfert galaxies, a class of spiral galaxies with very small bright nuclei whose spectra have high-excitation lines and in which the hydrogen emission lines in particular are very broad. The great width of these lines is an important point to which we shall return. Two of Seyfert's (1943) original list of a dozen objects are radio sources. Burbidge, Burbidge, and Sandage (1963) have suggested that they are manifestations of the same kind of nuclear violent events that give rise to radio sources, but perhaps on a smaller scale.

For the cosmological problem, the discovery of the quasi-stellar sources has already led to the observation of the greatest redshift yet measured, that for 3C147 (Schmidt and Matthews 1964), and, owing to their high optical luminosity, these objects may enable the redshift-distance relation to be extended to much greater distances.

II. DEFINITION OF ULTRAVIOLET SPECTRAL REGION

The spectral region we are considering is taken to be from 912 A (the Lyman limit) up to the ozone cut-off in the earth's atmosphere, around 3000 A. Actually, owing to the high atmospheric extinction just longward of 3000 A, it is profitable to extend this a little because relatively few ground-based observations of galaxies have been made between 3000 and 3300 A. Also, as we shall see when considering distant galaxies with large redshifts, there is a tie-in between what is normally unobservable from the ground and the usual optical region of $3300 < \lambda < 7000$. Shortward of 912 A, the opacity of interstellar hydrogen in our own Galaxy is very great, until one reaches $\lambda \leq 15$ A, as can be seen from the calculations of Aller (1959) and Strom and Strom (1961).

III. LINE RADIATION TO BE EXPECTED FROM GALAXIES

In the optical region, the integrated emission-line spectra of normal external galaxies are similar to low-excitation diffuse nebulae in our own Galaxy. The ionizing radiation is more dilute than in strong H II regions in our Galaxy like the Orion Nebula, and the average electron density is considerably lower. Consequently we see most generally the lines of Hα (Hβ is not very often seen on low dispersion spectra; the Balmer decrement is steep); [O II], [N II], and [S II]. Lines of [O III] are seen much less often than those of [O II], in sharp distinction from planetary nebulae. Therefore, in the ultraviolet we should expect the Lyman series of hydrogen, and lines from the first or second stage of ionization of common elements (C, N, O, Ne, Mg, Si, S), in permitted or forbidden transitions whose lower level is the ground state and whose upper level, excited by electron collision, is not too high - i.e., we might expect the most profitable region to study to be 1300 - 3000 A.

Code (1960) and Aller (1961) published lists of emission lines to be expected between 912 and 3000 A in planetary nebulae. Aller showed that the strongest lines to be expected would be permitted rather than forbidden transitions. Osterbrock (1963) published an extensive list, calculating the contribution to the relative intensities due to the collisional excitation strengths and to the downward transition probabilities of the lines. Bearing in mind that the average excitation in external galaxies is lower than in planetaries, the list of lines shown in Table 1, taken from the sources quoted above, would be the most likely to be found. The blend of the Mg II λ2800 lines has of course already been found in the spectra of some quasi-stellar sources where it is redshifted enough to fall into the spectral region accessible from the ground.

In the abnormal galaxies, a very wide range of ionization sometimes occurs, particularly in the Seyfert galaxies; lines of [O I] and [Fe VII], for example, both appear in the optical region. Thus the additional lines of S IV, N V, Si IV, and C IV, listed at the bottom of Table 1, should be found in Seyfert galaxies; of these, the Si IV and C IV should be the strongest.

IV. PASSAGE OF LINE RADIATION FROM SOURCE TO OBSERVER: PROBLEM OF OBSERVING LYMAN α

Since most of the lines in Table 1 are permitted transitions to the ground state, there is the problem of the optical depth in this line radiation to be considered, during the passage of the radiation from its point of emission to the observer. The problem is, of course, most acute for the Lyman α line of hydrogen, and yet that is the line we would first like to consider, because of its great observed strength in the solar ultraviolet spectrum, and because of the strength of the Balmer lines in the emitting gas in external galaxies. The problem of observing Lyman α may be divided into three parts: (1) Can the radiation leave the source; (2) Can it traverse the intergalactic space; and (3) Can it penetrate our Galaxy? Let us consider the third problem first. This has been discussed by Osterbrock (1962), Münch (1962), and more recently by Cook (1963). The optical depth in Lyman α due to the H I in our Galaxy is enormous. The half thickness at the position of the sun is $\tau_0 \approx 4 \times 10^7$. Münch, taking this average value, and supposing the H I gas to have macroscopic motions of 8 km/sec root mean square velocity, estimated that we would only see Lyman α radiation that was shifted from the zero velocity position by greater than 1000 km/sec. Fortunately, this still puts a very large number of galaxies within range of observation, since a good proportion of the galaxies no further distant than the Virgo cluster have redshift velocities > 1000 km/sec. A more detailed calculation by Cook, in which he took the observed optical thickness of neutral atomic hydrogen in various directions in our Galaxy from the 21-cm data, showed that this velocity restriction could be relaxed in appropriate directions to v > 375 km/sec (corresponding to $\Delta\lambda > 1.5$ A). Even in the local group of galaxies, the approaching end of M 31 might be observable, since there the rotational velocity adds to the mean approach velocity of the galaxy as a whole and the violet shift $\Delta\lambda > 1.5$ A.

To answer the second question, concerning the passage of Lyman α radiation through intergalactic space, we need to know the density and temperature of intergalactic hydrogen, and at present only certain limits can be set on these. The 21-cm data set an upper limit of 2×10^{-29} gm/cm^3 on the density of neutral atomic hydrogen (Davies and Jennison 1964; Gould and Sciama 1964). Direct comparison shows that a path length of 100 pc through our Galaxy with a mean density of 10^{-24} gm/cm^3 would be equivalent to an intergalactic path length of 5×10^6 pc at the limiting density. At a distance of 5×10^6 pc the Hubble velocity would be +500 km/sec and the corresponding wavelength shift of Lyman α would be 2 A.

If there is neutral intergalactic hydrogen, its root mean square velocity may be of the same order of magnitude as that of field galaxies, an uncertain quantity which probably lies around 300 km/sec, in comparison with the value of 8 km/sec taken for interstellar H I in our Galaxy. Also, such gas could be distributed either uniformly or in clouds. Even if there is neutral hydrogen at a density near the upper limit set by the null 21-cm observations, it will probably not cause complete absorption of Lyman α emitted by external galaxies, because of the probable velocity dispersion of the gas and the cumulative redshift. The problem may be turned around: if Lyman α is emitted from external galaxies, the observation of a superimposed absorption profile due to intergalactic gas should prove a very sensitive tool for determining the density, distribution, and velocity dispersion of the gas.

Intergalactic hydrogen, if present, could be partially or totally ionized. The upper limit to the density in this case would again be 2×10^{-29} gm/cm^3, the value obtained from most cosmological models. At this density, the upper limit to the temperature is 5×10^6 °K (Gould and Burbidge 1963). An ionized intergalactic component would behave like the H II component in our own Galaxy, at greatly reduced density, and we discuss this next.

The third question, concerning the escape of Lyman α radiation from the emitting source, is a difficult one to answer. In a source of great optical depth, where each Lyman α quantum is scattered a very large number of times on its way out of the source, as discussed by Münch (1962) and by Osterbrock (1962), the Lyman α radiation may be totally converted to 2-quantum emission so that very little of the Lyman α generated within the source would ever escape from the surface. The following equations show the process we are discussing:

Following	$H(1s) + L\alpha \rightarrow H(2p)$
we can have	$H(2p) + H^+ \rightarrow H(2s) + H^+$
or	$H(2p) + e^- \rightarrow H(2s) + e^-$
and then	$H(2s) \rightarrow H(1s) + 2\ h\nu$ in continuum.

As Münch and Osterbrock have pointed out, if we had only to consider coherent scattering, very little radiation would in fact escape, but actually the scattering is mainly non-coherent, so that much more radiation would escape than would seem at first sight to be the case. This is because the Lyman α line will be Doppler-broadened by the line-of-sight velocities of the emitting atoms. Then a quantum absorbed at the central frequency has a finite chance of being re-emitted in the wings. In their discussions, Osterbrock and Münch showed that, taking the Lyman α line to be broadened only by thermal Doppler broadening at an electron temperature of 10^4 °K, there would not be much conversion of Lyman α to two-quantum radiation for an optical depth $\tau = 10^6$. Applying this argument to H II regions in an external galaxy, we see that those regions on the near side of the galaxy might be observable, although for those on the far side, where the emitted radiation has to pass through a considerable optical depth in H I regions in the galaxy in question, we should expect complete absorption if the galaxy possessed a neutral hydrogen component similar to that in our own. The problem will have ultimately to be treated by setting up the detailed equation of transfer for Lyman α radiation with partially non-coherent scattering, and this has not yet been done.

Let us now discuss the chances of observing Lyman α emission from the various types of galaxy. Let us consider first the normal galaxies of types E, S0, and Sa. Here the radiation comes mainly from red giant stars and main sequence stars of types no hotter than the sun. Such stars may well possess extended chromospheres and coronae. There will be no shadowing of the stars one by another; even through the central region of an elliptical galaxy, a line of sight through a given star will pass right through the galaxy without encountering another star. Let us suppose there are 10^{12} stars of this type in a typical massive elliptical, S0, or Sa galaxy with a large central stellar bulge containing very little matter that is not condensed into stars. For such a galaxy, at a distance of 10^7 pc corresponding to a redshift of order 1000 km/sec, if every star radiates the same amount of Lyman α radiation as the sun, the ratio of Lyman α radiation received by the observer to the amount received from the sun would then simply be:

$$10^{12} \times \left\{\frac{1 \text{ a.u.}}{10^7 \text{ pc}}\right\}^2 \approx 10^{-13}; \quad \text{then} \quad \text{Flux} \approx 7 \times 10^{-13} \text{ erg cm}^{-2} \text{ sec}^{-1}.$$

As to the escape of the radiation from the galaxy, no elliptical galaxies have yet been detected in the 21-cm line from neutral hydrogen. There is, however, ionized hydrogen in the central regions of some of these types of galaxies. But here we have an additional factor helping the escape of the radiation, namely, the stars in the centers of elliptical galaxies have a large velocity dispersion. The root mean square velocity for the most massive objects may run up to 400 or 500 km/sec. Further, there are indications that the ionized gas may have a smaller velocity dispersion than the stars. Therefore the entire flux of Lyman α produced by all the stars of solar type and cooler will probably escape from such galaxies.

In the normal spiral and irregular galaxies, the regions that may be observed will be H II regions on the near side to the observer. The escape of the radiation from the source will be governed by the same considerations as apply in H II regions in our own Galaxy, and a more detailed treatment of the problem of transfer of Lyman α radiation through a gaseous nebula will have to be developed before the treatment by Osterbrock and Münch can be improved on. Among the objects with redshifts greater than a value in the range v = +375 to +1000 km/sec, those spirals and irregulars with plenty of H II regions but not much neutral hydrogen offer the best chance of observing Lyman α. The velocity dispersion and therefore the line breadth are greatest in the central regions. Further, in M 31 where detailed studies are available, the 21-cm observations indicate that the neutral hydrogen is concentrated near the spiral arms and outer parts and avoids the central region. Therefore the central regions of those galaxies like M 51 (NGC 5194) which have extensive H II regions in their centers (Burbidge and Burbidge 1964) would be the best candidates for observation.

In the abnormal galaxies, many of the radio sources and also the Seyfert galaxies have very strong emission lines. The quasi-stellar sources and particularly the Seyfert galaxies have also very broad emission lines, with velocity dispersions running up to several thousand km/sec. The escape of Lyman α radiation is, as we have seen, helped by such large velocity dispersions. If there is an appreciable component of neutral hydrogen with a lesser velocity dispersion than the gas that is giving rise to the emission lines (as is suggested by the occurrence of relatively weak and narrow [O I] lines together with the very intense and broad Balmer lines in Seyfert galaxies), then Lyman α may appear as a broad widely separated pair of emission lines, instead of a single line; i.e., the center of the line may not escape but the wings may well do so.

Table 2 lists some observed or estimated total emitted energies in the Balmer α line in galaxies ranging from the most abnormal type (the quasi-stellar object 3C273) to an estimate for a normal Sc spiral. Now in 3C273, Oke (1964) has made the usual assumption that each Balmer photon produces one Lyman α photon. He has not attempted to solve an equation of transfer for the Lyman α radiation, but has made the assumption that 2/3 of the Lyman α quanta produced throughout the object will escape from it, 1/3 being converted to two-quantum emission. This amount of two-quantum emission was compatible with his measures of the continuum of 3C273. This led him to the estimate of 2.8×10^{45} erg/sec for the energy in Lyman α leaving 3C273, i.e., a factor 20 times the measured Balmer α energy.

Let us now make the further assumption that the Lyman α emission in all the other objects in Table 2 is also 20 times the Balmer α emission. This is a very crude assumption, but it will enable us to have some idea of the comparative fluxes of representative objects at the appropriate distances. Choosing 2×10^7 pc and 10^7 pc, respectively, as suitable distances for a typical Seyfert galaxy and a normal Sc spiral (the latter corresponds to the limitation that the redshift should exceed 1000 km/sec), the Lyman α fluxes that might be received by the observer are given in Table 3. For objects much more distant than 3C273, the calculation would differ according to the cosmological model used; for 3C273 the appropriate correction is not large enough to affect the crude estimate in Table 3. In the case of M 82, given in Table 3, the redshift of the galaxy is only 300 km/sec relative to the local standard of rest so that it should be unobservable because of absorption in our own Galaxy even if we take the limitation set by Cook. It is interesting, however, to note that the Seyfert galaxies, which comprise only ~ 1% of all spirals, should be much stronger Lyman α emitters even at twice the minimum permitted distance.

V. REDSHIFT MEASUREMENTS AND THE COSMOLOGICAL QUESTION

Because of the high optical luminosity of the nearest of the quasi-stellar objects, 3C273, we may already be looking at some objects with large redshifts among the 17th and 18th magnitude star-like images for which tentative identifications with radio sources have been made but for which optical spectra have not yet been obtained (Ryle and Sandage 1964; Sandage 1964). A computation of the possible apparent magnitudes of objects like 3C273 at redshifts z = 1 and 2, for various cosmological models, shows this, as follows.

The distances which must be used in deriving apparent magnitudes for various values of z depend on the cosmological models; the appropriate formulae are given by Sandage (1961), and are:

$$m_{bol} = 5 \log \frac{1}{q_o^2} \left\{ q_o z + (q_o - 1) \left[(1 + 2 q_o z)^{\frac{1}{2}} - 1 \right] \right\} + C \qquad (1)$$

for evolutionary models with the cosmical constant $\Lambda = 0$ and the deceleration parameter $q_o > 0$. For $q_o = 0$,

$$m_{bol} = 5 \log \left\{ z \left(1 + \tfrac{1}{2} z\right) \right\} + C, \qquad (2)$$

and for the steady-state model,

$$m_{bol} = 5 \log \left\{ z (1 + z) \right\} + C. \qquad (3)$$

Since the magnitudes are actually measured in the visual or photographic range, there is an additional factor to be included, the well-known K-term (Sandage 1961 and references given there). This depends on the form of the function giving the variation with frequency of the power emitted by the source, so that:

$$m_{observed} = m_{true} + K. \qquad (4)$$

Oke (1964) has found that the energy radiated by 3C273 per unit frequency interval, F_ν, corrected for redshift, when plotted against frequency ν, gives an extremely flat curve, which he interprets as being produced by free-free emission from high-temperature hydrogen gas. If this is so, then the K correction in equation (4) arises only from the band-width correction due to the compression of a bandwidth $d\nu_o$ at ν_o to the redshifted $d\nu = d\nu_o/(1 + z)$ at redshift z, and K in equation (4) will be negative. (For normal galaxies, as shown by Sandage (1961), the K correction is positive). If the emission from the ultraviolet region of 3C273 is not free-free emission, but, for example, synchrotron radiation, as considered by Greenstein and Schmidt (1964), then the value of (-K) will be smaller. Let us take two possible values for the K correction, zero and that given by the bandwidth correction for F_ν independent of ν. Then we have:

$$\begin{aligned} m_{observed} &= m_{true} \text{ for } K = 0 \\ m_{observed} &= m_{true} - 2.5 \log (1 + z) \text{ for free-free emission.} \end{aligned} \qquad (5)$$

The apparent visual magnitude of 3C273 is 12.7 (Oke 1964), and its redshift z is 0.158 (Schmidt 1963). These give an absolute magnitude near -26. We will take -25 as a standard absolute magnitude, and compute the apparent magnitudes for redshifts z = 1 and 2, for the two cases given by equation (5), and for four cosmological models, namely, the steady-state model and the evolutionary models with the cosmical constant $\Lambda = 0$ and the deceleration parameter q_o equal to 0, $+\frac{1}{2}$, and +1. We have

$$\begin{aligned} m &= -25 - 5 + 5 \log (cH^{-1}) + 5 \log f(z) + K \\ &= +17.4 + 5 \log f(z) + K \end{aligned} \qquad (6)$$

where f(z) is given by equations (1), (2), and (3). Table 4 gives the results. From the values for z = 1, we see that, according to the cosmological model, several of the objects already tentatively identified with point sources of radiation, for which redshifts have not yet been determined, may fall into this region; even for z = 2 redshifts of objects at the apparent magnitudes listed might not be impossible to observe. For z = 1, Lyman α is shifted to λ2432, and for z = 2, Lyman α moves to λ3648, i.e., well into the spectral region that is accessible from ground-based instruments.

Thus we see that the problem of obtaining an ultraviolet spectrum both of a planetary nebula and of 3C273 itself is of prime importance in the question of making identifications and measuring redshifts in some of the objects which may be quasi-stellar objects at large redshifts. We urgently need to know what the observed spectrum of a gaseous nebula in the region λ1000 - 3000A looks like. In addition, flux measurements in the ultraviolet continuum of 3C273 should enable us to distinguish between Oke's high-temperature model with free-free emission and Greenstein and Schmidt's model with synchrotron radiation.

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TABLE 1

STRONGEST ULTRAVIOLET EMISSION LINES EXPECTED
IN SPECTRA OF EXTERNAL GALAXIES

Element	Wavelength (A)	Transition
[S III]	1021	$^3P - ^3P^o$
H I	1026	Lyman β
N II	1084-6	$^3P - ^3D^o$
S III	1190-4	$^3P - ^3D^o$
S III	1201	$^3P - ^3D^o$
Si III	1206	$^1S - ^1P^o$
H I	1216	Lyman α
S II	1250-54	$^4S^o - ^4P$
S II	1260	$^4S^o - ^4P$
Si II	1260-65	$^2P^o - ^2D$
Si II	1305-9	$^2P^o - ^2S$
C II	1334-6	$^2P^o - ^2D$
Si II	1808	$^2P^o - ^2D$
Si II	1817	$^2P^o - ^2D$
Mg II	2792-2804	$\begin{cases} ^2S - ^2P^o \\ ^2P^o - ^2D \end{cases}$
S IV	1073	$^2P^o - ^2D$
N V	1239-43	$^2S - ^2P^o$
Si IV	1394-1403	$^2S - ^2P^o$
C IV	1548-51	$^2S - ^2P^o$

TABLE 2

ENERGY RADIATED IN BALMER Hα LINE IN SOME GALAXIES

Galaxy	Energy Emitted in Line at Source (erg sec^{-1})
3C273	1.4×10^{44} (Oke 1964)
Cyg A	$\sim 10^{44}$ (estimate based on Baade and Minkowski (1954))
NGC 1068 (Seyfert Galaxy)	2.2×10^{41} (Osterbrock and Parker)*
M 82	2×10^{40} (Lynds and Sandage 1963)
Normal Sc	$\sim 10^{39}$ (my estimate)

* I am very grateful to Dr. Osterbrock for permission to quote this result in advance of publication.

TABLE 3

POSSIBLE FLUXES IN LYMAN α AT OBSERVER

Galaxy	Distance (Mpc)	Flux ($erg\ cm^{-2}\ sec^{-1}$)
3C273	500	1×10^{-10}
Cyg A	200	4×10^{-10}
Average Seyfert Galaxy	20	1×10^{-10}
M 82	3	4×10^{-10}
Normal Sc	10	2×10^{-12}

TABLE 4

APPARENT MAGNITUDES OF STANDARD OBJECT
FOR VARIOUS COSMOLOGICAL MODELS

Model	K = 0		K = -2.5 log (1 + z)	
	z = 1	z = 2	z = 1	z = 2
Steady-state	18.9	21.3	18.2	20.1
$\Lambda = 0$, $q_o = 0$	18.3	20.4	17.6	19.2
$\Lambda = 0$, $q_o = \frac{1}{2}$	17.8	19.4	17.1	18.2
$\Lambda = 0$, $q_o = 1$	17.4	18.9	16.7	17.8