THE ASTROPHYSICAL JOURNAL, Vol. 158, November 1969

SOME MODELS FOR THE EMISSION-LINE REGION OF 3C 48*

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Received 1969 March 17

ABSTRACT

Models for the emission-line region of 3C 48 are derived by using calculated ionization distributions. Estimates are given of the parameters that characterize the emission-line region and of the relative abundance of H, He, O, Ne, and Mg.

I. INTRODUCTION

We describe the results of some calculations of the ionization distribution in the emission-line region of the quasi-stellar radio source 3C 48 ($Z_{\text{emission}} = 0.37$ [Greenstein and Matthews 1963]). This work is a continuation of our earlier study of 3C 273 (Bahcall and Kozlovsky 1969). Previous models of the emission-line regions of quasi-stellar sources in which the ionization distribution was assumed not calculated have been described by Greenstein and Schmidt (1964), Shklovsky (1965), Osterbrock and Parker (1966), and Burbidge *et al.* (1966). The new feature that is present in the spectrum of 3C 48 that was not observed in 3C 273 is the strong line due to the highly forbidden transition [O II] λ3727. We find that the required strength of λ3727 cannot be obtained in our models unless (*a*) the oxygen abundance is an order of magnitude larger than the solar value or (*b*) the O II emission comes from a different region than the O III, Ne V, and Mg II lines. The possibility that more than one region would be required to explain the spectra of quasi-stellar sources was discussed earlier by Osterbrock and Parker (1966) and Woltjer (1967). It would be informative to measure the shapes of emission lines in 3C 48 to see if there is any indication that, for example, the lines [O II] λ3727 and [O III] λ5007 arise in different regions.

In § II we summarize briefly some of the characteristics of our models, and in § III we present the results of calculations of the emission-line strengths for models that are homogeneous spheres of filaments. In § IV we describe the results of similar calculations carried out for hollow spheres (shell models). The results of considering two-region models are described in § V. Our principal results are summarized in § VI.

II. BASIC FEATURES

Our models, following Greenstein and Schmidt (1964), consist of a small central objects that emits a strong continuum flux and a large gas cloud that surrounds the central source and emits the observed line radiation. We assume that the continuum intensity in

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* Supported in part by the National Science Foundation [GP-9433, GP-9114] and the Office of Naval Research [Nonr-220(47)] at the California Institute of Technology.

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the far-ultraviolet emitted by the central source can be obtained from the observed intensity in the visual part of the spectrum by a smooth extrapolation that is not very steep. In particular we assume that the central object emits a continuum flux $F_\nu d\nu$, in ergs sec^{-1}, that has the form

$$F_\nu = F_0(\lambda/2500\ \text{Å})^{1.4}\,, \qquad \lambda < 2500\ \text{Å}\,, \tag{1}$$

where (cf. Oke 1966) $F_0 = 7 \times 10^{29}$ ergs sec^{-1}. The calculated ionization distributions for 3C 273 (cf. Bahcall and Kozlovsky 1969) were found not to be very sensitive to the precise value of F_0 and the exponent in equation (1). They are completely insensitive to the long-wavelength form of F_ν which we have therefore grossly characterized by equation (1). The radius of the line-emitting region was chosen so that the calculated strength of Mg II λ2798 agreed with the observed line strength. Further details of the models, including the atomic parameters used, the assumed "solar" composition (Zirin 1966), and the calculational method, can be found in Bahcall and Kozlovsky (1969).

TABLE 1

HOMOGENEOUS MODELS

Ion	λ_0 (Å)	Model 1 ($n_e = 10^5$ cm^{-3}; $R = 42.5$ pc)	Model 2 ($n_e = 5 \times 10^4$ cm^{-3}; $R = 62.5$ pc)	Model 3 ($n_e = 2.5 \times 10^4$ cm^{-3}; $R = 102$ pc)	Observed Intensity
Hβ	4861	6.6	6.3	6.0	6.4 G.S. 17 Oke
He II	4686	0.39	0.37	0.37	<2 Oke (1969)
Mg II	2798	3.5	3.4	3.5	3.1 G.S. 3.3 Oke
[O II]	3727	0.09	0.11	0.14	3.3 G.S.
[O III]	5007	12	11	8	40 Oke
[Ne III]	3869	0.19	0.18	0.16	<2 Oke (1969)
[Ne V]	3426	5.6	5.4	5.0	1.7 G.S.

NOTE.—Emission-line strengths are given in units of 10^{42} ergs sec^{-1} for three spherical models. The temperature in all cases is 1.7×10^4 ° K, and the filling factor is $\epsilon = 10^{-3}$. The ratio of helium to hydrogen by number is 7×10^{-3}; all other abundances are equal to their solar values. Here n_e is the electron number density and R is the radius of the sphere. The last column contains the observed values of the line strengths (also in 10^{42} ergs sec^{-1}); the abbreviation G.S. indicates values taken from Greenstein and Schmidt (1964), and Oke indicates values taken from Oke (1966).

III. HOMOGENEOUS MODELS

We first investigated models of the kind that were found satisfactory for 3C 273, namely, homogeneous spheres containing line-emitting filaments all at the same temperature and density. In Table 1 we present some results calculated for three models with different values for the density of the filaments. We see from Table 1 that even for a particle density as low as 2.5×10^4 cm^{-3}, for which collisional de-excitation of the excited ^2D state of O II is small, the calculated energy in [O II] λ3727 is less than the observed value by more than a factor of ten. The agreement between the observed and calculated luminosities for the other lines is satisfactory and similar to that obtained for 3C 273. Table 1 was calculated for a ratio of helium to hydrogen by number of 7×10^{-3}. This is a factor of 10 lower than the most recent estimates of the solar ratio of helium to hydrogen inferred from solar-model calculations (Bahcall, Bahcall, and Ulrich 1969); a similarly low value for the helium abundance was required in our models of 3C 273. For both 3C 48 and 3C 233 the absence of He II λ4686 in the observed spectrum requires a low helium abundance in our models, although for 3C 48 the observations are not sensitive enough to say whether or not the required deficiency is as large as a factor of 10.

We tried cutting off exponentially the extrapolated form of the photon flux at various frequencies in order to obtain a model in which the calculated strength of [O II] λ3727 was closer to the observed value. We were unable to obtain a satisfactory model in this way, since no matter where we cut off the flux, additional discrepancies were produced between the calculated and observed line intensities. For example, a cutoff in the range 10–20 eV caused Hβ to be much too small and made the line [Ne v] λ3426 disappear completely. A cutoff in the range 40–100 eV actually decreased the calculated strength of λ3727, since Mg II is more strongly affected by the cutoff than O II; the radius of the emission-line region was fixed, as stated earlier, by matching the calculated and observed strengths of Mg II λ2798.

IV. SHELL MODELS

We then investigated shell models (hollow spheres) in which the line-emitting material is concentrated in a shell around the central object (as suggested by Shklovsky 1965). Such models are plausible since it is reasonable to expect that the material close to the central object will be blown away by the strong radiation pressure from the continuum source. The material in the shells was still assumed to be in filaments all of which had the same temperature and density. In Table 2 we present some results calculated with the aid of three representative shell models (models 4, 5, and 6). In models 4 and 5, the [O II] λ3727 line is even weaker than in the corresponding homogeneous models. Model 6 has a low particle density ($n = 9 \times 10^3$ cm^{-3}) and a large outer radius ($R_2 = 190$ pc), but the calculated strength of the [O II] line is still an order of magnitude lower than the observed value.

TABLE 2

SHELL MODELS

Ion	λ_0 (Å)	Model 4 ($n_e = 10^5$ cm^{-3}; $R_1 = 42.5$ pc; $R_2 = 53$ pc)	Model 5 ($n_e = 5 \times 10^4$ cm^{-3}; $R_1 = 65.5$ pc; $R_2 = 80$ pc)	Model 6 ($n_e = 9 \times 10^3$ cm^{-3}; $R_1 = 62.5$ pc; $R_2 = 190$ pc)	Observed Intensity*
Hβ	4861	5.8	5.1	5.6	6.4 G.S. 17 Oke
He II	4686	0.36	0.33	0.34	<2 Oke (1969)
Mg II	2798	3.5	3.2	3.3	3.1 G.S. 3.3 Oke
[O II]	3727	0.06	0.04	0.2	3.3 G.S.
[O III]	5007	11	7	7	40 Oke
[Ne III]	3869	0.18	0.16	0.16	<2 Oke (1969)
[Ne V]	3426	5.5	5.4	5.6	1.7 G.S.

NOTE.—Emission-line strengths are given in units of 10^{42} ergs sec^{-1} for three shell models. Here R_1 is the inner radius of the shell and R_2 is the outer radius. The temperature, filling factor, chemical abundances, and references for observed intensities are all the same as for the models described in Table 1.

* See Table 1 for key to abbreviations.

One possible solution to the problem of the strength of the [O II] λ3727 line is suggested by the results for model 6 given in Table 2. Note that the calculated strengths, in this model, of both [O II] λ3727 and [O III] λ5007 are smaller than their observed values by a factor ~5–10. Thus a reasonable fit to the observed line strengths can be obtained by adopting model 6 and assuming that the oxygen abundance relative to hydrogen is a factor of 5–10 times larger in 3C 48 than in the Sun. The strengths of the neon lines are roughly the same in all our models (cf. Tables 1 and 2) and are consistent with a solar ratio of neon to hydrogen. The results are also very roughly consistent with a solar ratio of magnesium to hydrogen.

A similar solution could also be obtained with a low-density homogeneous model that had a high oxygen abundance. We have not constructed such a model in detail because

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the computer time required is rather long, but extrapolations of our other homogeneous models indicate that it would not be too different from the acceptable shell model, number 6 of Table 2.

V. TWO-REGION MODELS

We were also able to construct more complicated models in which the calculated and observed line strengths were in agreement *and* the abundance ratio of oxygen to hydrogen in 3C 48 was the same as in the Sun. These models consisted of two regions: (1) an inner region which was one of the homogeneous or shell models discussed in §§ II and III, and (2) a surrounding outer layer in which the ionization was primarily collisional. In the inner region, the continuum radiation from the central object is primarily responsible for the ionization structure. Only at the outer edge of the inner region has the ionizing, ultraviolet radiation been sufficiently depleted so that collisional ionization is important. We chose a uniform density and a uniform temperature for the outer layer such that only [O II] λ3727 and Hβ were produced in this region. We assumed for this layer the kind of steady state that exists in the solar corona, i.e., the ionization structure was determined by equating collisional ionization to recombinations.

TABLE 3

OUTER REGIONS

Ion	λ_0 (Å)	Outer Region 1 ($n_e = 5 \times 10^3$ cm^{-3}; $R_{\text{outer}} = 73$ pc)	Outer Region 2 ($n_e = 7 \times 10^3$ cm^{-3}; $R_{\text{outer}} = 71.5$ pc)	Outer Region 3 ($n_e = 1 \times 10^4$ cm^{-3}; $R_{\text{outer}} = 69$ pc)
Hβ.	4861	16	18	22
Mg II ..	2798	0.11	0.13	0.15
[O II].	3727	3.3	3.3	3.3
[O III].. ..	5007	0.03	0.04	0.04

NOTE.—Emission-line strengths are given in units of 10^{42} ergs sec^{-1} for three outer regions constructed so as to fit onto model 2 of Table 1. The temperature of the outer regions is 2.5×10^4 ° K, and the outer radius is denoted by R_{outer}. The intensity of the neon lines produced in this region is negligible.

In Table 3 we present some results for outer atmospheres for model 2 of Table 1. The inner radius was fixed at 65.5 pc in order to join on the homogeneous model, and the outer radii were determined by requiring that the calculated energy in the O II line equal the observed value. The temperature in the outer region was chosen to be 2.5×10^4 ° K in order that there be no contribution to the line Mg II λ2798 from this area. At 2.5×10^4 ° K, almost all of the oxygen is in the form of O II, but very little of the Mg is in the form of Mg II (House 1964). The ions Ne III and Ne V are also quite rare at this temperature. It was not necessary to assume a filamentary structure in this region, since the opacity to electron scattering is small.

A satisfactory fit to the observed line strengths is obtained if, for example, the homogeneous model 2 of Table 1 is combined with the outer region 1 of Table 3. The results are compared with observations in Table 4. Note that the agreement between calculated and observed strengths of the Hβ line, as well as the O II line, is much improved in the combined model.

The two-region model described above is not unique. In particular one could obtain results similar to those shown in Table 4 by combining the shell model 5 of Table 2 with the outer region 1 of Table 3. In either case, the characteristic parameters are approximately the same. Since the results for the three outer regions given in Table 3 are all approximately the same, one could, in fact, use equally well any of the three outer regions shown.

VI. SUMMARY

The observed emission-line spectrum can be represented satisfactorily by two kinds of models that we have investigated. First, either a sphere of filaments or a shell is satisfactory if the oxygen abundance relative to hydrogen is a factor of 5–10 greater than the solar value. The required density is then $\sim 10^4$ cm^{-3}, the outer radius $\sim 2 \times 10^2$ pc, and the filling factor $\epsilon \sim 10^{-3}$. Second, one can also fit the observed line strength with an abundance ratio of oxygen to hydrogen that is the same as the solar value if the emission of [O II] λ3727 is assumed to originate in a region that is shielded from the strong ionizing flux of the central source and is at a temperature $\sim 2.5 \times 10^4$ ° K. In both classes of models, the ratio of helium to hydrogen must be less than the solar value by a factor of 2 or more, and the abundances of neon and magnesium are approximately equal to their solar values. Our most striking result can be summarized as follows: We have not yet encountered a case in our analysis of either 3C 273 or 3C 48 in which the abundance of any element relative to hydrogen was required to differ by more than a factor of 10 from its solar value.

TABLE 4

COMBINED INTENSITIES FROM TWO REGIONS

Ion	λ_0 (Å)	Combined Intensity	Observed Intensity*
Hβ . .	4861	22	6.4 G.S. 17 Oke
He II . .	4686	0.4	<2 Oke (1969)
Mg II.	2798	3.5	3.1 G.S. 3.3 Oke
[O II].	3727	3.4	3.3 G.S.
[O III] .	5007	11	40 Oke
[Ne III] .	3869	0.2	<2 Oke (1969)
[Ne V] .	3426	5.4	1.7 G.S.

NOTE.—The calculated emission-line strengths from model 2 of Table 1 plus the Outer Region 1 of Table 2 are compared with the observed strengths All intensities are given in units of 10^{42} ergs sec^{-1}

* See Table 1 for key to abbreviations

All of our models are optically thick for wavelengths greater than 912 Å. Hence the observed continuum is expected, on the basis of our models, to change its form at 912 Å.

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