THE ASTROPHYSICAL JOURNAL, 233:1–4, 1979 October 1

THE 1400 Å EMISSION FEATURE IN QUASI-STELLAR OBJECTS

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Received 1979 March 23; accepted 1979 April 9

ABSTRACT

Analysis of data for about 100 quasars allows the rest wavelength of the 1400 Å emission feature to be determined to ±0.5 Å rms, showing that the principal contributor (85 ± 9% rms) is O IV] λ1402.5, rather than Si IV λ1397. The observed strength of the feature is consistent with predictions of photoionization models and cosmic abundances of C, N, O, and Si if the collisional cross section of O IV] λ1402.5 is about three times the uncertain value in current use.

Subject headings: line identifications — quasars

I. INTRODUCTION

A broad emission feature with rest wavelength near 1400 Å is visible in the spectra of most quasi-stellar objects (hereafter "quasars") that have sufficiently large redshifts ($z \gtrsim 1.5$). Its strength is typically 10% the strength of Lα, which is the strongest emission line seen in such objects. Because the line is weaker than Lα or C IV λ1549, an accurate wavelength measurement is generally not possible for an individual object and the line is traditionally attributed to Si IV λ1397, O IV] λ1406, or a blend of these two at 1400 Å. In § II attention is drawn to the generally overlooked revision of the effective wavelength of O IV] from 1406 Å to 1402.5 Å, and in § III an analysis of published data for about 100 quasars allows the rest wavelength to be determined with rms accuracy of 0.5 Å, and shows that O IV] is the principal contributor. Implications for models of quasar emission-line regions are discussed in § IV.

II. REVISED WAVELENGTH OF THE O IV] FEATURE

Osterbrock (1963) discussed the expected UV emission spectrum of a gaseous nebula, and his results have been widely used. He included the five lines that make up the semiforbidden O IV] feature, with an effective wavelength of 1407 Å, mentioning that the wavelengths were uncertain. Observations of the Sun by Burton, Ridgeley, and Wilson (1967) gave wavelengths of the four strongest components of O IV], with rms accuracy 0.05 Å. These wavelengths are all ~5.2 Å smaller than those given by Osterbrock (1963), and were confirmed within 0.1 Å by laboratory measurements made by Bromander (1969), whose wavelengths are accurate to ~0.01 Å. Flower and Nussbaumer's (1975) results show that the effective wavelength of the O IV] feature varies by less than 0.1 Å for electron densities $n_e = 10^8$–10^{12} cm^{-3}, and that for $n_e = 10^9$ cm^{-3} the effective wavelength is 1402.46 Å. The new wavelengths were listed by Osterbrock (1971), but have been ignored by nearly all quasar spectroscopists since then.

III. WAVELENGTH OF THE 1400 Å FEATURE

Even if the observed wavelength of the 1400 Å feature can be determined only to ±25 Å rms in a single quasar spectrum, its occurrence in ~100 objects should reduce this uncertainty to ±2.5 Å rms, or ±1 Å rms in the rest frame (since the line is seen only for redshifts $\gtrsim$1.5). This was considered sufficiently encouraging to carry out a literature search for published wavelengths of the 1400 Å feature (the list is obtainable from the authors upon request). One technique considered was to use the published emission-line redshift (recalculated, if necessary, without using the 1400 Å feature) to determine the rest wavelength, but it seemed presumptuous and dangerous to reanalyze the published data, since observers rarely specify the weights used in calculating the redshifts. Furthermore, the profile of Lα in high-redshift objects is systematically distorted by absorption blueward of the line center, and sometimes by uncertain blending with N V λ1240 on the red side. It was therefore decided to use only the C IV λ1549 line, which is usually observable in the same spectrum and which is not systematically distorted. The only disadvantage is that there is an additional uncertainty arising from the measured wavelength of the λ1549 line in each quasar, but this is generally much smaller than the uncertainty in the 1400 Å feature, and the result should not be biased.

Although the literature search revealed 158 measurements of the 1400 Å feature in 125 objects, some of them could not be used, because the C IV line either was not measured or was very uncertain, or because the 1400 Å feature was stated to be only marginally visible, of very uncertain wavelength, or otherwise suspect. Nevertheless, there remain 100 measurements, after averaging independent measurements of the feature in the same object, and the results are displayed as a histogram of rest wavelengths in Figure 1. Using an effective wavelength of 1549.06 Å for the C IV line, the mean value of rest wavelength λ_0 for the 1400 Å

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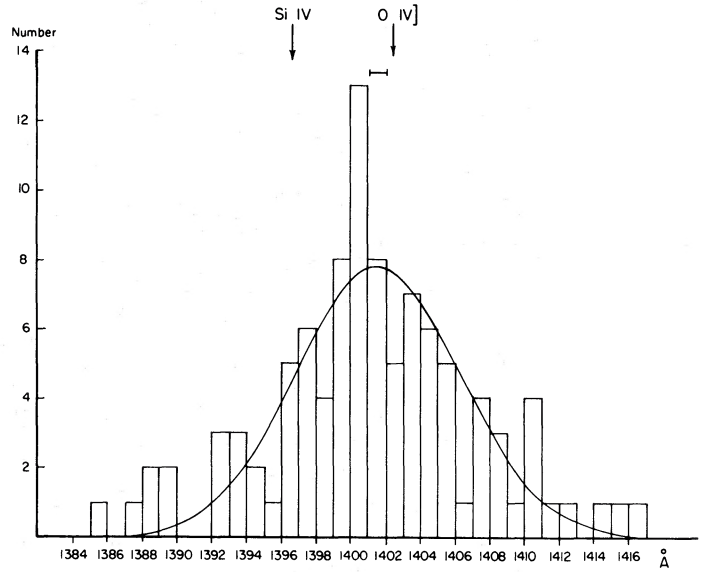

FIG. 1.—Distribution of rest wavelength λ_0 of the 1400 Å emission feature in 100 quasars. The mean value and $\pm 1\ \sigma$ uncertainty are shown as the horizontal bar, and the rest wavelengths of O IV] λ1402.5 and Si IV λ1396.8 are shown by the vertical arrows. The solid curve is a Gaussian with the same mean (1401.62 Å) and dispersion (4.68 Å) as the 91 values between $\lambda_0 = 1390$ and $\lambda_0 = 1414$ Å.

feature is $\langle\lambda_0\rangle = 1401.22 \pm 0.61$ Å rms. If the extreme values are omitted from Figure 1 (specifically, $\lambda_0 <$ 1390 Å and $>$ 1414 Å), the value for the remaining 91 objects is $\langle\lambda_0\rangle = 1401.62 \pm 0.49$ Å rms. The full curve in Figure 1 is the Gaussian with the same mean and dispersion as these 91 values. The mean is nearly 10 σ away from the Si IV effective wavelength (1396.76 Å) and, incidentally, from the earlier values of 1406 Å or 1407 Å for O IV], but the result is clearly consistent with the hypothesis that the 1400 Å feature can be attributed entirely to O IV] at the revised rest wavelength of 1402.5 Å. Formally, O IV] contributes 85 ± 9% rms of the line. As a 2 σ upper limit, it contributes more than 68% to the intensity of the 1400 Å feature (equal contributions, e.g., would give $\lambda_0 = 1399.6$ Å, which is excluded at the 4 σ level).

The present sample of quasars contains nearly equal numbers of radio-emitting and radio-quiet objects, and the mean values of λ_0 differ by only 0.45 ± 1.25 Å rms. Likewise, there is no significant trend of λ_0 with emission-line redshift—the correlation coefficient is +0.10, significant at only the 1.0 σ level.

Baldwin and Netzer (1978) tried to separate the 1400 Å feature into its components, using the C IV λ1549 line profile, and a deblending technique. In three of their 13 objects, Si IV λ1397 was estimated to contribute $\gtrsim$30% to the feature (with large uncertainties in each case). In the other 10 objects the observed feature seemed to be mainly O IV] λ1402, or a hopeless blend. In only one object (4C 29.50) was the line consistent with being entirely Si IV λ1397. These results are consistent with our finding based on a much larger sample.

Finally, it should be pointed out that there is little hope of resolving the individual components of the O IV] multiplet in quasars. If the components are smoothed with a Gaussian function having $\sigma = 3$ Å (corresponding to a Doppler motion of about 650 km s^{-1}), the resulting profile shows only one peak, and is a close fit to a Gaussian centered at 1402.46 Å, with $\sigma = 3.9$ Å. Similarly, the Si IV doublet, whose separation is 9.0 Å, shows only one peak in the combined profile if smoothed with $\sigma \gtrsim 4$ Å, so the fact that the 1400 Å feature is not generally observed to be double is not by itself evidence against attributing the 1400 Å feature entirely to Si IV.

IV. THE LINE STRENGTH AND ITS IMPLICATIONS FOR QUASAR MODELS

We consider now the strength of the 1400 Å feature ("λ1400") and its consequences for models of the emission-line regions in quasars. Taking both Si IV and O IV] contributions to the line, we find the following mean values: $I(\lambda1400)$:I(C IV λ1549):$I(\mathrm{L}\alpha)$ = 0.11:0.36:1.00 (Osmer and Smith 1977), 0.06:0.28:1.00 (Osmer 1977), and 0.13:0.41:1.00 (Baldwin and Netzer 1978). These measurements seem typical of others in the literature. The λ1400 feature therefore has 10% of the intensity of Lα, and ~30% of the intensity of C IV λ1549. Photoionization models of quasar emission lines are usually quite successful in predicting the relative strengths of the UV lines. However, all the detailed models published so far (excluding constant temperature models, which are too simplified, or models with large amounts of internal dust), such as those by Davidson (1972), MacAlpine (1972), Shields (1976), Baldwin and Netzer (1978), Netzer and Davidson (1979), and Shuder and MacAlpine (1979) predict the λ1400 line to be much weaker than is observed, by a factor of about 2–4, i.e.,

$$I(\lambda 1400)/I(\mathrm{C\,IV}\ \lambda 1549) \lesssim 0.1\,.$$

Most of the calculations also predict O IV] λ1402 to be stronger than Si IV λ1397 by a small factor. The situation was noted and discussed by Baldwin and Netzer (1978).

We note in passing a common difficulty in most photoionization calculations concerning the strong high-excitation lines of O VI λ1035 and N V λ1240. These are calculated to be too weak by a large factor in all single-component models (Netzer 1976; Davidson 1977; Baldwin and Netzer 1978). This is probably not related to the problem of the λ1400 line, since the excitation conditions for O IV] λ1402 or Si IV λ1397 are very different from those of O VI or N V. The λ1400 line is formed in an optically thick component, where other lines like C IV λ1549, C III] λ1909, and N IV] λ1486 originate. We assume for this component the acceptable value of the ionizing parameter $U_1 \equiv F_1/n_e h \approx 2 \times 10^8\ \mathrm{cm\ s^{-1}}$, where F_1 is the ionizing flux at the Lyman edge (e.g., Davidson 1972, 1977), but our results are sensitive neither to this assumption nor to the shape of the ionizing continuum. We consider both Si IV λ1397 and O IV] λ1402 as possible contributors to the λ1400 line, and look for other emission lines that come from the same region, in order to provide model-independent line ratios. This approach was used by Shields (1976) to study the heavy-element abundances in quasars, and was shown to be successful for several line ratios.

Consider first the Si IV λ1397 line. The ionization potentials of silicon and nitrogen suggest the coexistence of Si IV and N III under nearly the same conditions in the He^+ zone. We therefore assume Si/N ≡ Si IV/N III in this zone. Using cross sections from Osterbrock and Wallace (1977) we find:

$$\frac{I(\mathrm{Si\,IV}\ \lambda 1397)}{I(\mathrm{N\,III]}\ \lambda 1750)} \approx 27(\mathrm{Si/N}) \exp(-2.08/T_4), \ldots, \quad (1)$$

where T_4 is the electron temperature in units 10^4 K. Recent transition-probability calculations for the intercombination line of N III] λ1750 (Nussbaumer and Storey 1979) indicate a critical density $\sim 2 \times 10^{10}\ \mathrm{cm^{-3}}$, which is high enough to justify neglecting collisional deexcitation effects in equation (1). An obvious limitation is the temperature dependence of the above ratio.

N III] λ1750 is very weak and difficult to measure in individual objects, but its average observed value is quite useful for our purpose. The observations by Baldwin and Netzer (1978) suggest a mean value of

$$\frac{I(\lambda 1400)}{I(\mathrm{N\,III]}\ \lambda 1750)} \gtrsim 4.5$$

for five quasars, with possibly higher values for seven others (here and later we exclude B2 1225+31, whose lines are extremely broad and hard to measure). Assuming that the temperature is around 15,000 K and that Si IV is the main contributor to the line, this would require (Si/N) ≈ 0.67, about 2.5 times the cosmic value (Cameron 1973). A similar analysis for the

$$\frac{\mathrm{Si\,IV}\ \lambda 1397}{\mathrm{O\,III]}\ \lambda 1664}$$

line ratio can be done but is not as useful, since the creation zones of both lines do not exactly overlap, and since O III] λ1664 may be susceptible to collisional deexcitation effects. However, when carried out it tends to indicate that the only way to make Si IV so strong is by having unusually high Si/O (~2.7 times the cosmic abundance). A comparison with C III] λ1909 (which may be sensitive to collisional deexcitation effects) gives similar results. We see no reason why Si would be overabundant in quasars with respect to other elements, and are not aware of any other observational support for this. Also, there is no indication that the collision cross section for Si IV λ1397 will be in error by such a large factor, which would probably show up in analysis of solar-flare observations. We conclude therefore that Si IV λ1397 contributes, in most cases, only a small amount to the λ1400 line, in accordance with our wavelength measurements in § III.

Can O IV] λ1402 contribute most of the flux in the observed line? The best comparison is with N IV] λ1486 (note, however, that the N IV zone is somewhat larger than the O IV zone since ionization of N^{++} can proceed beyond the He^{++}-He^{+} ionization front, while only excited-level ionization of O^{++} can take place there). Using the same analysis, and Ω(O IV] λ1402) = 1.4 (Osterbrock and Wallace 1977), we find:

$$\frac{I(\mathrm{O\,IV]}\ \lambda 1402)}{I(\mathrm{N\,IV]}\ \lambda 1486)} \approx 0.28\left(\frac{\mathrm{O}}{\mathrm{N}}\right) \exp(-0.58/T_4)\,. \quad (2)$$

This ratio is less sensitive to temperature changes, and we again assume $T_4 = 1.5$. From Baldwin and Netzer (1978) we find a mean observed value of

$$\frac{I(\lambda 1400)}{I(\mathrm{N\,IV]}\ \lambda 1486)} \approx 3.3\,,$$

which would indicate (O/N) ~ 3 times its cosmic value. A similar, although more temperature-dependent, test can be performed with C IV λ1549. This gives (O/C) ~ 4–5 times the solar value if O IV] λ1402 is the main contributor to the λ1400 line. Detailed photoionization calculations support the qualitative picture drawn here (see, e.g., Baldwin and Netzer 1978, Table 3), and it seems that the only way to produce O IV] λ1402 as strong as the observed λ1400 line is if oxygen is overabundant relative to nitrogen and carbon by a factor of order 3–4, compared with its cosmic value. This, if correct, is in conflict with some recent calculations and observations of quasars. For instance, Shields (1976) and Baldwin and Netzer (1978) found that C, N, and O in quasars are probably *at least* as abundant as in the Sun, with some indications of nitrogen being further enhanced. (O/C) seems to have its cosmic value in such analyses. That (N/O) is relatively high is indirectly indicated by, for example, the N V λ1240/O VI λ1035 line ratio. In addition, the good consistency of the strength of many weak lines, including those of oxygen (N III] λ1750, O III] λ1664, N IV] λ1486, C III] λ1909, etc.) relative to He II λ1640, suggests that carbon, nitrogen, and oxygen have solar or higher abundances relative to helium (Baldwin and Netzer 1978) and that O/C is close to its solar value.[2] Higher temperatures and different spectra are called for if O is enhanced relative to C and N but not relative to hydrogen. This is not entirely impossible, but it would give less satisfactory agreement with observations. Relative excess of oxygen only is hard to explain on the basis of acceptable stellar evolution theories. Since there are two or more observed lines for each of C, N, and O in at least several objects, and since all their relative strengths agree quite well except that of λ1400, it is more natural to suspect this line, rather than the rest of the spectrum.

In all the above we have used the published value Ω(O IV] λ1402) = 1.4. This value was obtained by Osterbrock and Wallace (1977) by extrapolating near-threshold calculations for C II] λ2326 and N III] λ1750 by Jackson (1973). Direct calculations of Ω(O IV] λ1402) by Flower and Nussbaumer (1975) are available only at high energies. Linear extrapolation of Flower and Nussbaumer's cross sections gives values close to those given by Osterbrock and Wallace, and consistent with solar-flare observations, where $T \sim 10^5$ K (U. Feldman, private communication). However, the presence of strong resonances in the collision strength near threshold (e.g., Jackson 1973, Figs. 1*a* and 1*b*) may change this situation considerably, since the relatively low temperatures in quasars indicate that the largest contributions to the collision strength are from these energies. Integration over the (unknown) resonances is complicated, and Nussbaumer (private communication cited by Osterbrock and Wallace 1977) found, when doing so, a value for Ω that is about 3 times larger than the one used here. If indeed Ω(O IV] λ1402) $\approx$ 4 instead of 1.4, then most or all of the difficulties mentioned earlier disappear. The λ1400 line is then mainly due to O IV] λ1402, and its relative strength compared with the N IV] λ1486 and C IV λ1549 lines agrees with most observations, and with cosmic or higher abundances of C, N, and O.

Some potential complications ought to be borne in mind. First, as discussed by Baldwin and Netzer (1978), ionization from the $^1D_2$ excited level of O^{++} can significantly affect the O III/O IV population, and thus the strength of O IV] λ1402. Second, $H + O^{++} \rightarrow H^+ + O^+$ charge exchange, possibly with a high rate (Butler, Bender, and Dalgarno 1979), combined with the Auger process, can be important if the ionizing continuum is rather flat. We have carried out some detailed photoionization calculations with all these effects included (for a description of the program, see Baldwin and Netzer 1978), and indeed found better agreement with observations using the new value of Ω, for a variety of values of U_1 and spectral shape. Note that an increase of Ω by a factor of $\sim$3 would simply enhance the O IV] λ1402 line by a similar factor, since C IV λ1549 is still the main coolant in the O IV zone. This correction could therefore be applied to most published calculations.

We therefore conclude that (i) the wavelength of the 1400 Å feature in quasars indicates that O IV] λ1402, rather than Si IV λ1397, is the principal ($85 \pm 9\%$ rms) contributor, and (ii) this is consistent with existing models of the emission-line regions in quasars if the collisional cross section of O IV] has been underestimated by a factor of about 3. A less likely explanation for the strength of O IV] is that oxygen is overabundant with respect to carbon, nitrogen, and perhaps hydrogen, by a factor of $\sim$3.

We thank Dr. U. Feldman for calculating for us some useful collisional rates for O IV] λ1402. D. W. acknowledges support from the National Science Foundation (grant AST 76-81338 A01).

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[2] Recently there have been some attempts to explain quasars' spectra by including effects like reddening by internal or external dust and collisional deexcitation processes (for more details and references see Shuder and MacAlpine 1979; Netzer and Davidson 1979). Some of these ideas also involve ionizing continua different from those usually assumed. Most of our analysis will not change under such circumstances since it is based on the comparison of different intercombination and recombination lines that are very close in wavelength and not affected by large optical depth effects.

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