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SPLITTINGS IN QUASAR ABSORPTION LINES

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ABSTRACT

It is shown that the apparent constancy of the splitting between quasar absorption lines observed by Boksenberg and Sargent could be understood if the typical velocity in the absorbing material were somewhat less than the observing resolution (estimated to be 100 km s^{-1}). If this interpretation were correct, then there should be many more redshifts that are split with velocity separations that are less than 100 km s^{-1} than have been so far observed at velocity separations of the order of 150 km s^{-1}. The above conclusions are independent of whether or not the absorption lines originate close to, or very far away from, the quasar. Some results are presented for a specific model in which the splittings are supposed due to absorption in halos or clouds surrounding galaxies or small groups of galaxies and some tests of this model are suggested. The model parameters are consistent with recent radio observations of H I clouds or halos that extend far from their parent galaxies.

Subject headings: galaxies — line profiles — quasi-stellar sources or objects

I. INTRODUCTION

Boksenberg and Sargent (1975) have drawn special attention to a fascinating new phenomenon that appears in at least seven cases in the high-resolution spectra of the quasar PKS 0237−23: the splitting of the observed absorption redshifts into separate systems each separated by a characteristic velocity of the order of 150 km s^{-1}. The splitting of some absorption lines into close but separate redshift systems was first found in the high-resolution spectra of TON 1530 by Morton and Morton (1972) and in the spectra of Markarian 132 by Morton and Richstone (1973). A similar splitting has been suggested by Wingert (1975) for a pair of redshift systems in the spectrum of PHL 957.

In this *Letter* we show, with the aid of a simple mathematical model, that one can have an apparently constant measured velocity splitting that results from observations of a broad velocity distribution with a spectroscopic resolution that is less than the typical velocity. The small dispersion in the measured values of the splittings observed by Boksenberg and Sargent (1975) could be understood on the basis of a broad velocity distribution if the typical velocity were of the order of 50 to 75 km s^{-1} and the Boksenberg-Sargent spectroscopic resolution were of the order of 100 km s^{-1}. This conclusion is independent of the particular model we consider subsequently (condensations in galactic halos); it is valid for any explanation in which the relative velocities of the subsystems are not quantized (e.g., a swarm of clouds in a quasar atmosphere). We then show that a range of parameters that might plausibly characterize a large galactic halo (radius $\sim 10^2$ kpc, column density $\gtrsim 10^{18}$ cm^{-2}, velocities ~ 100 km s^{-1}) can account for the observed lines and their splittings, and is consistent with recent H I radio observations of extended clouds. Finally, we list some possible observational tests of our interpretation.

II. THE "MAGIC" SPLITTING

The seven "certain" cases of velocity splitting reported by Boksenberg and Sargent (1975) have a standard deviation about the mean of a single measurement of $\sigma(v) = 23$ km s^{-1}. The large value (~ 6) for the ratio of average splitting to standard deviation, as well as the close agreement between the observed standard deviation and that expected from measuring errors alone, led Boksenberg and Sargent to suggest that the value of about 140 km s^{-1} may be a constant "magic" splitting.

We do not know, however, what selection effects enter into the identification of closely split systems of absorption lines. It is clear that the splitting must be large enough to be resolved but not so large as to be unrecognized as a pair. There is also some tendency to give added credence to a candidate redshift that is very close to an established redshift (see e.g., Wingert 1975). As an example of the role of interpretation in deciding what is a splitting, we note that Boksenberg and Sargent have reported, among others, three closely spaced pairs of redshifts (1.6558, 1.6570), (1.6698, 1.6714), and (1.6731, 1.6743). They computed the splittings between the pairs within each parenthesis, all equal to $\Delta z = 0.0014 \pm 0.0002$ or approximately 150 km s^{-1}. If instead we first average the numbers within each parenthesis (as would be appropriate, e.g., if each parenthesis referred to a separate galaxy or other physical unit) and then compute the splittings between parentheses, we obtain $\Delta z = 0.0142$, 0.00315, or velocity splittings of 1,600 and 350 km s^{-1}.

Putting aside for the moment the question of whether or not the observations require an approximately constant velocity splitting, we consider the mathematical question of what constraints a presumed broad velocity distribution must satisfy in order to give the appearance of a constant splitting. In calculating what standard deviation we expect for the observed splittings from various models, we assume that velocity splittings less than about 100 km s^{-1} would not have been found in most cases by Boksenberg and Sargent (1975). This is suggested by the fact that out of the 73 lines found at their highest resolution only one pair was closer than 1 Å (and one of the pair of lines in question was listed as of 0 strength, i.e., of uncertain reliability).

Suppose (for illustration) that the individual absorbers have Maxwellian velocity distributions, $f(v_x) \propto \exp(-v_x^2/\Delta^2)$. The total root mean squared velocity, $v_{\rm RMS}$, is $(3/2)^{1/2}\Delta$. The average *measured* splitting in velocity will then be

$$\langle \Delta v\rangle = \left[\int_\beta^\infty dv\, v \exp(-v^2/2\Delta^2) \Big/ \int_\beta^\infty dv \exp(-v^2/2\Delta^2) \right], \tag{1}$$

where β is the minimum velocity splitting that can be measured due to the finite resolution of the spectrographic system. The value of $\langle \Delta v\rangle$ can be calculated easily from equation (1); one finds

$$\langle \Delta v\rangle = 2^{1/2}\Delta \exp(-\beta^2/2\Delta^2)/\Gamma(\tfrac{1}{2}, \beta^2/2\Delta^2)\,. \tag{2}$$

Here $\Gamma(a, x)$ is the usual incomplete gamma-function. Thus for large values of (β/Δ), $\langle \Delta v\rangle \sim \beta$. The standard deviation of the measured velocity splitting can also be easily calculated for the Maxwellian model; one finds

$$\sigma = \langle \Delta v\rangle\, [(\Gamma(\tfrac{1}{2}, \beta^2/2\Delta^2)\Gamma(3/2, \beta^2/2\Delta^2) \times \exp(\beta^2/\Delta^2) - 1]^{1/2}\,. \tag{3}$$

For large values of β/Δ, one finds

$$\langle \Delta v\rangle/\sigma \sim (\beta/\Delta)^2\,. \tag{4}$$

Thus the observational results of Boksenberg and Sargent imply that $\beta \gtrsim 2.5\ \Delta$, i.e.,

$$\beta \gtrsim 2v_{\rm RMS}\,. \tag{5}$$

In the Maxwellian model, one would expect to find occasional cases of three closely spaced redshifts. One can show that for such triple systems (two splittings) the average splitting of each close pair is again β in the limit of $\beta^2 \gg \Delta^2$.

The above results show that one can achieve the appearance of a constant splitting in a broad velocity distribution provided the resolution of the spectrographic detection system for split lines is less than the typical velocity. Physically, this result is obvious: the probability of having two velocities separated by more than the instrumental resolution is exponentially small so that the highest probability for an observable line occurs for a velocity separation equal to the instrumental resolution. One can derive a similar result for a flat velocity distribution (uniform probability) provided (once again) the spread in velocities is comparable with the instrumental width. Considering only the Boksenberg-Sargent data, the observations seem to require a typical velocity ~50 to 75 km s^{-1}.

III. GALACTIC HALOS

In what follows, we show that the observations of split quasar absorption lines can be fitted by assuming galactic halos with plausible typical values: radius ~100 kpc, H II column density ~$10^{18.5}$ cm^{-2}, velocity $\lesssim$100 km s^{-1}, and halo mass less than one-half the total mass. These numbers represent only a modest extrapolation from recent radio observations (e.g., of rotation curves [Roberts and Rots 1973; Oort 1974; Rots and Shane 1974; Allen, Goss, and van Woerden 1973]) which typically extend to radii ~25 kpc, H I column densities ~$10^{20.5}$ cm^{-2}, and rotational velocities ~100 km s^{-1}. Moreover, Mathewson, Cleary, and Murray (1975) and Wright (1974) report H I observations of clouds, with the properties we require to explain the quasar absorption lines, that extend far from the Sculptor group and M33, respectively. The observed H I clouds in the Sculptor group have, for example, a linear extent of 180 kpc and an H I column density greater than 10^{19} atoms cm^{-2}. Also Kormendy and Bahcall (1974) have shown that many spiral galaxies and small groups of galaxies have very large but faint optical halos (dimensions greater than 100 kpc); this result complements the earlier demonstration by Arp and Bertola (1969) and de Vaucouleurs (1969) that bright ellipticals have large halos. Support for the existence of a hot interstellar medium of the kind originally proposed by Spitzer (1956) for galactic halos has been obtained by *Copernicus* studies of the ultraviolet O VI lines (see Jenkins and Meloy 1974; York 1974; Rogerson *et al.* 1973).

It is important to verify that the predicted number of absorption redshift systems is at least consistent with the available astronomical data. We report below the results of a specific calculation, but the reader will see that a number of assumptions and parameters could be changed while still arranging that the final result be consistent with the observed number of redshifts. We assume an isothermal halo out to a fixed radius, $R_{\rm halo}$, which is taken proportional to $M_{\rm galaxy}{}^{1/3}$ (in what follows we shall scale halo radii relative to the radius of M31, an average galaxy for our purposes). We adopt Schechter's (1974) estimate for the galaxy mass function, $q_0 = \frac{1}{2}$, $H_0 = 50$ km s^{-1} Mpc,$^{-1}$ and assume that galaxy radii are independent of redshift. The total number, P, of galaxy halos that produce redshift systems between $z_{\rm em}$ and z_c is then (cf. Bahcall and Spitzer 1969)

$$P = 1.6 \left[\frac{R_{\rm halo}(\rm M31)}{100\ \rm kpc}\right]^2 \times [(1 + z_{\rm em})^{3/2} - (1 + z_c)^{3/2}]\,. \tag{6}$$

The optical depth of the galaxy halo to a resonant absorption line with f-value, $f_{\rm abs}$, corresponding to an ion containing a fraction $\epsilon M_{\rm halo}$ of the total halo mass is

$$\tau \sim \epsilon \times 10^{7.5} f_{\rm abs}(100\ {\rm kpc}/R_{\rm halo})^2 \times (M_{\rm halo}/1 \times 10^{11} M_\odot)\,. \tag{7}$$

Assuming, for illustration only, that 1 percent of the halo mass is in gas, and that 10^{-4} of the gas mass is in the form of C IV, then τ(C IV) $\sim$ several. Thus there may be easily several absorption systems per galaxy halo. The average distance (weighted as radius^{-1}) at which absorption occurs is $\frac{3}{4}R_{\text{halo}}$, which is, according to our previous estimates, of the order of 75 kpc for galaxies of about the mass of M31. The typical rotational velocity for galaxies of this mass is (see Roberts and Rots 1973; Rubin and Ford 1970) about 1.5×10^2 km s^{-1} at a radius of the order of 20 kpc. Thus it is not unreasonable to expect, as suggested by the observations of Boksenberg and Sargent (1975), a typical velocity,

$$v_{\text{halo}} \approx 50\text{–}75 \text{ km s}^{-1}, \qquad (8)$$

at a radius $\sim$75 kpc provided that the halo mass does not contribute very much to the total galaxy mass.

IV. DISCUSSION

If the apparent constancy of the redshift splittings is due to the accidental coincidence between the typical velocity resolution in the observations and the characteristic velocity of condensations in some gravitating system, then there must be many more examples of small splittings than have so far been observed in the range 100–150 km s^{-1}. A critical test of the ideas discussed in this note would be to observe PKS 0237−23 (or any other quasar which exhibits absorption-line splitting) at a resolution much better than 100 km s^{-1} (e.g., 50 km s^{-1}). It would also be of special interest to observe at the highest possible resolution the $z = 2.309$ absorption system in PHL 957 which Lowrance *et al.* (1972), Grewing and Strittmatter (1973), and Wingert (1975) have suggested might be due to an intervening galaxy. Should this redshift system exhibit split absorption lines (not with the magic splitting), it would be support for the ideas discussed in this *Letter*. Similar remarks apply to the $z = 0.6128$ absorption system in the quasar PHL 938 ($z_{\text{em}} = 1.95$, Burbidge, Lynds, and Stockton 1968; see also Bahcall 1971). Another possible way of discriminating between rival explanations for the observed splittings is to search for 21-cm absorption at approximately the same redshift as the optical absorption lines. Because the detectable H I column density is necessarily large with current detectors, the probability of detecting H I absorption is small on any hypothesis. However, the likelihood of detecting 21-cm absorption is much higher for material in a distant galaxy than it is for material near a luminous quasar (see Bahcall and Ekers 1969). Finally we should note that if (as suggested by Bahcall 1971) the Class I absorption lines, $|z_{\text{em}} - z_{\text{abs}}| \lesssim 10^{-2}$, originate relatively close to the quasar, then we would not necessarily expect splittings in these lines. However, split class I systems have been observed in PHL 957, TON 1530, and Markarian 132 (Morton and Morton 1972; Morton and Richstone 1973; Wingert 1975). It is possible that the split lines that have been observed in these cases are caused by galaxies rather close to the quasar, perhaps galaxies in a group or cluster containing the quasar. They might also be caused by the quasar's own galaxy halo, if a quasar is a disease or an event in a galaxy. Some support for this speculation has been provided by the recent observation of Wampler *et al.* (1975) of an emission-line nebulosity around 3C 48.

One can easily imagine versions of the basic idea that we have discussed in which, in some cases, the velocity splitting is much larger. For example, in some cases the absorption could occur in the halos of galaxies that are themselves in clusters or groups. In this case, a splitting of order 10^3 km s^{-1} might be observed. The results of Strittmatter *et al.* (1973) for 1331+170 ($z_{\text{em}} = 2.08$) could be interpreted in this way; they find two redshift systems at $z_{\text{abs}} = 1.775$ and 1.7851, corresponding to $\Delta v \approx 10^3$ km s^{-1}. Recall also that there is some evidence for splittings of 350 and 1600 km s^{-1} in the Boksenberg-Sargent data for PKS 0237−23, depending on how the splittings are calculated (cf. § II).

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