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Evidence Bearing on the Interaction of Gas and High-energy Particles in Quasi-stellar Objects

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Summary. Large fluxes of high-energy electrons are responsible for the non-thermal radio fluxes and probably the optical continua from compact sources in quasi-stellar objects. If they are accompanied by energetic fluxes of protons with energies $\gtrsim 100$ MeV, we expect that interaction with the gas that is responsible for the line spectra will lead to spallation. Among the primary spallation products is the element boron with the lines B III $\lambda 2066.3$ and B II $\lambda 1362.46$ which would be detectable in QSO spectra. These lines have been looked for in the spectra of a number of QSO's listed in Tables 1 and 2. They are absent, and by analyzing the ionization structure of the emitting and absorbing regions we find that the limit to the boron to carbon radio is $N(\mathrm{B})/N(\mathrm{C}) \leqq 1/15$. Since the composition of the gas is normal, and no boron can be detected we show:

(i) that the gas cannot have originated in the very central regions of the continuum source with sizes $\lesssim 1$ pc, since even exposure to large fluxes of protons for a short time (<1 year) would have led to gross changes in composition.

(ii) For a specific model, in which it is supposed that the proton flux diffuses through the emission-line region of the gas we find that in order that $N(\mathrm{B})/N(\mathrm{C}) \leqq 1/15$, the flux of protons with mean energy $\gtrsim 100$ MeV must be $\lesssim 4\ 10^{53}$ erg, or about 10^{-4} of the energy carried by the electrons in the most powerful continuum sources. With different models, more stringent limits could be set. It is concluded either that the proton flux is small, or that the particles do not interact significantly with the gas because they are ejected axisymmetrically and the ejection is confined to a very small solid angle. Such a geometry is suggested by the radio data.

Key words: quasistellar objects — abundances — high-energy particles

I. Introduction

The existence of compact powerful non-thermal optical and radio sources in QSO's and the clear demonstration that the radio sources at least are incoherent-synchrotron sources indicates that the central nuclei contain large fluxes of relativistic electrons (and positrons). On the assumption that the redshifts are cosmological, model calculations indicate that the energy involved in relativistic particles responsible for radio emission $\varepsilon_e \gg \varepsilon_{\mathrm{mag}} \approx 10^{53}-10^{58}$ erg (Burbidge et al., 1974). In the case of the radio sources, the measurement of the angular size together with the observed frequency at which the spectrum turns over due to synchrotron self-absorption, gives a direct estimate of the magnetic field and hence the energy contained in relativistic electrons in each of the sources.

The total energy involved in the fluxes of electrons responsible for the optical synchrotron continuum cannot be estimated as well because no angular size measurements can be made. However, we can make estimates of minimum energies involved by assuming an equipartition of energies between the magnetic fields and relativistic particles; these lead to energies in the range $10^{55}-10^{57}$ erg.

The non-thermal sources exhibit rapid variability of luminosity on timescales of a year or less, both in the radio as well as in the optical regions of the spectrum. VLBI measurements are most simply interpreted as showing that the radio sources are expanding. Now, the lifetime for energy loss through synchrotron emission for the electrons generating radio-waves in the QSO's exceeds 10^4 years. It is therefore clear that the rapid variability is likely to be due to the escape of particles rather than due to energy-loss processes. Thus, we are led to the idea that the relativistic particles in the non-thermal sources escape rapidly on timescales of years and hence they must be generated on similar timescales as long as the object has a compact component. In the case of the electrons responsible for the optical emission, we do not know what fraction of the energy is radiated

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before escape. However, it is reasonable to suppose that they also escape with a substantial part of their energy intact. The particle luminosities therefore lie in the range $10^{45}-10^{50}$ erg s^{-1}.

There is no direct evidence for the presence of a high-energy nucleonic component in the central non-thermal source of the QSO's. However, considerations of acceleration processes suggest that a large flux of high-energy protons and other nuclei may be present. In this paper we shall assume the energy contained in the nucleonic component ε_n is indeed equal to the energy contained in the relativistic electrons, ε_e, i.e. $\varepsilon_n \approx \varepsilon_e$. We shall for this assume that the energy ε_n resides mostly in protons of energy $E_p \gtrsim 100$ MeV.

The line spectra of the QSO's provide evidence that gas is also present. Analyses of the emission-line regions lead to the conclusion that they surround the non-thermal nucleus with a structure that may be shell-like or filamentary. Models which have been made to account for the emission-line spectra suggest that the particle densities cover a range from about 10^7-10^3 cm^{-3} with temperatures in the range 10^4-10^5 K (Bahcall and Kozlovsky, 1969a, b; MacAlpine, 1972; Chan and Burbidge, 1975; Baldwin, 1975). Dimensions of the region are typically about 10–100 pc (for cosmological distances) and the total mass involved is about $10^5\,M_\odot$. The volume is not completely filled by gas at these densities. The filling factor that is commonly obtained is about 10^4.

In addition to the emission-line region, many QSO's show absorption-line spectra which may be explained by supposing either that the absorbing gas is intrinsic to the QSO's or that it is due to intervening galaxies or intergalactic clouds. In many cases we are fairly sure that it is intrinsic to the QSO's (when $z_{\rm abs} \approx z_{\rm em}$, and for objects with broad absorption-line spectra), and we shall assume in what follows that the bulk of the absorption does arise in gas which is intrinsic to the QSO. While the abundance analyses that have been carried out are not very accurate, there is no evidence at present that there are large anomalies in composition in the emitting or the absorbing gas.

The natural model is then one in which both the emitting and the absorbing gas components have been ejected from the region of the central continuum source. A good case can be made for supposing that radiation driving is an important mechanism which accelerates and maintains the outward motion (Mushotzky et al., 1972; Kippenhahn et al., 1974, 1975).

The question that we address here is the extent to which the high-energy particles interact with the gas. In such an interaction, there will be two major effects. On the one hand the large amount of kinetic energy carried by the particles will, through collective effects, and through individual particle collisions, tend to heat up and drive out the gas (cf. Eilak and Caroff, 1976). On the other hand, the nucleonic component of the particle flux will, through collisions at high energy, modify the chemical composition through spallation reactions. It is this latter process that we shall be concerned with here.

On exposure to a flux of high-energy nucleons the common elements like C, N, O, Mg, Si and Fe which are abundantly produced in stellar nucleosynthesis will be broken down to lighter fragments and these will tend to fill up the valleys in the element distribution. If this process is allowed to proceed for a long time a smooth elemental distribution would result and the gas giving rise to the spectral lines in the QSO's will fail to exhibit the peaks at the magic numbers as displayed by the so-called "universal abundances" (Cameron, 1968).

Further, since the cross-section for spallation is a monotonically increasing function of the atomic weight of the target nucleus exposure to very large fluxes will produce a composition which is smoothly decreasing function of atomic weight.

On the other hand, exposure to milder fluxes of high-energy nucleons will lead only to a minor modification of the relative amounts of the more abundant elements like C, O, Mg, Si, Fe, etc., but there will be a dramatic build-up of the abundances of the rare elements like Li, Be, B, etc. The analogous build-up of these elements in the Galaxy is well known (Reeves, 1974).

Before we can go into a quantitative discussion of the effect of spallation, we need to specify the life-history of the gas. In the absence of detailed information, we make two extreme assumptions, one of which minimizes the spallation rates (Model A), and the other which maximizes the effect of spallation (Model B). In Model A it is assumed that the gas originates directly at a radial distance R_g, at the site of the emission-line formation; this gas exhibits turbulent velocities $U_t \approx 3000$ km s^{-1} a part of which may be radially directed $U_g \approx 1000$ km s^{-1}, so that the gas will have a typical residence time $T_G \approx R_g/U_g$. In Model B, we assume that the gas originates within the central continuum source and is swept out to the radius R_g where it condenses into the filamentary structures or clouds which give rise to the line spectra.

II. Spectroscopic Limits on the Abundance of Boron

As was mentioned in the previous section, the abundances of the rare elements Li, Be and B will be built up by spallation. In this section we describe the attempt to look for spectrum lines due to these elements in QSO's.

Investigation of the laboratory spectra of these elements shows that the best lines of any of those that we are likely to be able to observe in the ultraviolet spectra of QSO's are B III λ2066.3 and B II λ1362.46. B III λ2066 would be expected to be seen in emission and can be compared in intensity with C III] λ1909, while B II λ1362 might be seen in absorption and can be compared with C II λ1334.5.

We have looked in detail at high resolution spectra of a number of QSO's obtained by the groups involving some of us (J.B., A.B. and R.C.) at the Lick, Hale and Kitt Peak Observatories. In no case are we able to identify either of the features due to boron. Now we have that

$$l_1 = \frac{n(\mathrm{B}^{++})}{n(\mathrm{C}^{++})} = \frac{1}{\alpha}\frac{w(\mathrm{B\,III}\,\lambda 2066)}{w(\mathrm{C\,III}\,\lambda 1909)},$$

where α is the ratio of the transition probabilities. For an assumed temperature of 10^4 degrees, we estimate that $\alpha \simeq 7.5$. Thus, from Table 1 the most conservative upper limit to the numerical value of l_1 is $l_1 \leqq 1/15$.

Turning to the absorption-line ratio, B II λ1362.5 has a gf value of 1.1 and C II λ1334.5 has $gf = 0.26$. C^+ and B^+ both have ionization potentials very close to 25 eV. A complication which arises is that the C II* λ1335.7 fine structure line is often blended with the ground state feature, and this can contribute up to twice the optical depth of the λ1334.5 line (Grewing and Strittmatter, 1973).

We list in Table 2 the equivalent width of the C II λ1334.5 line as observed in some of these QSO's where it has been measured, and upper limits to the B II line equivalent widths. The C^+/B^+ number ratio is an underestimate, not only because the upper limits are only available for the B II line, but also because in the absence of velocity dispersion information we do not know if the C II line is optically thick. If the additional information is available, then the limits can improve dramatically above the upper limit for $C^+/B^+ > 10$–20 usually found here. For example, if we use Williams et al. (1975) model for the 3C 191 absorbing clouds, we have $n(\mathrm{C}^+) = 5.9\ 10^{-5}\ \mathrm{cm}^{-2}$, and $n(\mathrm{B}^+) \leqq 2\ 10^{-8}\ \mathrm{cm}^{-2}$, giving $n(\mathrm{C}^+)/n(\mathrm{B}^+) \geqq 300$. Also, in all cases, in arriving at our estimates we have assumed the largest possible contribution from the C II fine structure line, also in an optically thin approximation. For 3C 191 and PHL 1127 it is not resolved from the ground-state line, in 1331+170 it is marginally resolved, so an improved limit is used, and for PHL957 and B2 1225+31 very high (0.7 Å) resolution spectra are available so this difficulty does not arise.

Table 1. Emission-line region limits on the ratio of line strengths w(C III] λ 1909)/w (B III λ 2066)

Object	w(C III] λ 1909)/w (B III λ 2066)
PHL 938	>15
4 C 25.05	> 8
PKS 0424−13	> 7
0830+119	>15
BSO 1	>10
Ton 490	> 5
3 C 181	> 2
1215+114	> 4
1524+102	> 2
PHL 5200	> 5
1622+159	> 4
PHL 957	> 4

Now that we have made estimates of $n(\mathrm{B}^{++})/n(\mathrm{C}^{++}) \leqq l_1$ from the emission-line regions, and $n(\mathrm{B}^+)/n(\mathrm{C}^+) \leqq l_2$ from the absorption-line regions, we need to estimate $n(\mathrm{B})/n(\mathrm{C}) \leqq L$. To do this it is necessary to estimate the expected degree of ionization of boron in a gas whose general state of ionization can be worked out from the observed lines arising from the elements C, O, Mg, etc.

We argue first that the boron will be present as B^+, B^{++} and B^{+3} only. Since the ionization potential of neutral boron (8.29 eV) is much less than that of hydrogen (13.54 eV) and carbon (11.3 eV), no significant amounts of neutral boron are likely to be present. At the other extreme, the ionization potential of B^{+3} (259.3 eV) is so high that in regions where significant numbers of ions of ionization potential well under 100 eV exist, B^{+3} will not be converted to B^{+4} and will thus represent the end of the boron ionization chain.

Thus,

$$n(\mathrm{B}) = n(\mathrm{B}^+) + n(\mathrm{B}^{++}) + n(\mathrm{B}^{+3}) \leqq l_2\, n(\mathrm{C}^+) + l_1\, n(\mathrm{C}^{++}) + n(\mathrm{B}^{+3}).$$

Table 2. Absorption-line region limits on the line ratio

Object	z_{abs}	w (C II λ 1334)	w (B II λ 1362)	$n(\mathrm{C}^+)/n(\mathrm{B}^+)$	
3 C 191 $z_{em} = 1.956$	1.946	1.90	≦0.34	≧ 9[a]	Williams et al. (1975), Ap. J. **202**, 296
PHL 1127 $z_{em} = 1.991$	1.955	0.61	≦0.4	≧ 2[a]	Carswell et al. (1976), in preparation
1331+170 $z_{em} = 2.081$	1.7755	0.57[b]	≦0.11	≧20	Carswell et al. (1975), Ap. J. **196**, 351
	1.7851	0.33[b]	≦0.11	≧12	
B 2 1225+31 $z_{em} = 2.2$	1.7937	0.50	≦0.11	≧18	Sargent et al. (1976), in preparation
PHL 957 $z_{em} = 2.69$	1.7964	0.71	≦0.18	≧15	Wingert (1975), Ap. J. **198**, 267
	2.3085	0.45	≦0.12	≧15	Sargent et al. (1976) or later, in preparation

[a] Assumes fine structure line twice ground-state line
[b] Assuming contribution from C II * λ 1335.7 is half that of the ground-state line

Unfortunately, there are no lines due to transitions in B^{+3} which lie in the observable spectral window so that no direct limits on $n(B^{+3})$ can be set from observation. However, careful examination of ionization equilibrium calculations for photoionization by power-law spectra of a wide variety of spectral indices and high-energy cut-offs (Röser, 1976) indicates that in the range of ionization parameter (photon-energy density/mass-energy density) where C^{++} and C^{+3} coexist, $n(B^{++})/n(B)$ must be very near its maximum. This enables us to make the conservative estimate that the upper bound of $n(B^{+3})/n(B^{++})$ is of order unity, so that

$$n(B) \leqq l_2 n(C^+) + 2l_1 n(C^{++}).$$

The fact that strong C IV lines are observed indicates that neither $n(C^+)$ nor $n(C^{++})$ can be much larger than $n(C)/2$, and of course they may be much less than this. Putting these limits in, we find that

$$n(B) \leqq \frac{n(C)}{2}(l_2 + 2l_1),$$

i.e.

$$L \leqq \frac{l_2 + 2l_1}{2}.$$

Using the values of l_1 and l_2 estimated in Tables 1 and 2, we find that

$$L \leqq \frac{1}{2}\left(\frac{1}{15} + \frac{1}{30}\right) = \frac{1}{20}.$$

Since we have had to combine the results from Tables 1 and 2, we have clearly assumed that the gas in the emission- and absorption-line regions has the same composition and similar ionization structures and is intrinsic to the object. It is unfortunate that at present the data are insufficient to allow separate treatments of these two regions. Clearly in order to set tighter limits number ratios for all the ions from the same region would be required. However, this is the best that can be done at present and for the order-of-magnitude limits given here, the approximation used above appears to be adequate.

III. Composition Changes Due to Spallation Reactions

Following the discussion in Section I we assume that the total kinetic energy of the relativistic nucleonic component (mostly protons) in the central non-thermal source is comparable to that of the electrons generating the synchrotron radiation, i.e. $\varepsilon_{\text{electron}} \approx \varepsilon_{\text{nucleon}} \approx \varepsilon_{\text{proton}}$. We further assume that the energy spectra are similar and that the mean energy per particle $\bar{E}_n = \bar{E}_p \approx 100$ MeV. The particles escape from the central region, with a typical time constant τ_c, of ~ 1 year.

We now consider a volume into which a gas with normal chemical composition is injected at a rate S_i nuclei cm^{-3} s^{-1} for each nuclear species i. Then the variation in time of the density of nuclei of the i^{th} kind, N_i, due to escape and spallation is given by the equation

$$\frac{dn(i)}{dt} = -\frac{n(i)}{T} - \frac{n(i) b_i \varrho_p \bar{\beta} c}{E_p} + \sum_{j>1} \sigma_{ij} \bar{\beta} \frac{c\varrho_p}{E_p} n(j) + S_i \ldots \tag{1}$$

where

$n(i)$ = number density of nuclei of the i^{th} kind,
T = effective time constant for the removal of gas from the volume,
b_i = total cross-section for spallation,
$\bar{\beta}c$ = mean velocity of the protons with mean energy $\bar{E}_p$
σ_{ij} = partial cross-section for the spallation of nuclei of the j^{th} kind into the i^{th} kind,
S_i = average rate of injection of nuclei of the i^{th} kind, and
ϱ_p = the total kinetic energy density of the nucleon component.

We consider steady state solutions to Equation (1) ($dn(i)/dt = 0$) under two different assumptions presented as Case 1 and Case 2 below.

Case 1: Since S_i exhibits peaks at the "magic numbers", and the heights of these peaks drop off rather steeply with increasing atomic number beyond oxygen, we can neglect the contributions due to spallation of the heavier nuclei and write

$$n(i) \simeq S_i \left\{\frac{T}{1 + b_i \varrho_p \beta c T/\bar{E}_p}\right\} \tag{2}$$

for the more abundant elements C, O, Si, Fe, etc. Thus, for immense exposures $n(i) \sim S_i/b_i \propto S_i/A^{2/3}$, where A is the atomic weight of the nucleus.

Case 2: For elements like Li, Be and B which are very rare, $S_i \approx 0$, so that

$$n(i) \simeq \left\{\frac{T}{1 + b_i \varrho_p \bar{\beta} c T/\bar{E}_p}\right\} \sum_{j>i} \sigma_{ij} \bar{\beta} c \varrho_p N_j / \bar{E}_p . \tag{3}$$

Since spectroscopic limits are available only for boron, we can further simplify Equation (3) by considering only carbon and oxygen in the summation. Spallation of oxygen and carbon contribute about equally to the abundance of boron through the reactions:

$$p + {}^{12}C \to {}^{11}B + 2p$$
$$p + {}^{12}C \to {}^{10}B + 2p + n$$
$$p + {}^{16}O \to {}^{11}B + 4p + 2n$$
$$p + {}^{16}O \to {}^{10}B + 4p + 3n .$$

The threshold for these reactions is ~ 30 MeV and the cross-section for the spallation of carbon to boron is ~ 100 mb. The cross-section for the spallation of oxygen is somewhat smaller, ~ 50 mb, but it contributes equally because $n(\mathrm{O})=2n(\mathrm{C})$. Making these substitutions Equation (3) becomes

$$\frac{n(\mathrm{B})}{n(\mathrm{C})}=\frac{2\sigma_{ij}\bar{\beta}c\varrho_p T/\bar{E}_p}{1+b_{\mathrm{B}}\varrho_p\bar{\beta}cT/\bar{E}_p}. \quad (4)$$

We see here that as T or ϱ_p becomes very large the ratio $n(\mathrm{B})/n(\mathrm{C})$ saturates to a value $2\sigma_{ij}/b_{\mathrm{B}}\approx 1.1$ (with $\sigma_{ij}\approx 100$ mb and $b_{\mathrm{B}}\approx 180$ mb). When $n(\mathrm{B})/n(\mathrm{C})$ is small compared with unity, Equation (4) becomes

$$\left.\begin{aligned}\frac{n(\mathrm{B})}{n(\mathrm{C})}&=2\sigma_{\mathrm{C-B}}\bar{\beta}c\frac{\varrho_p}{E_p}T\\ &=2\sigma_{\mathrm{C-B}}\bar{\beta}cn_pT,\end{aligned}\right\} \quad (5)$$

where n_p is the number density of high-energy protons.

From Section II we can now put $n(\mathrm{B})/n(\mathrm{C})=L\leqq 1/20$, and putting $\sigma_{\mathrm{C-B}}=10^{-25}\,\mathrm{cm}^2$, $\bar{E}_p=100$ MeV, $\bar{\beta}c=1.3\;10^{10}\,\mathrm{cm\,s^{-1}}$ we find that

$$\varrho_pT\leqq 4\;10^9\,\mathrm{erg\,cm^{-3}\,s},$$

or

$$n_pT\leqq 2.5\;10^{13}\,\mathrm{cm^{-3}\,s}.$$

IV. Limits on the Flux of Protons Interacting with the Gas

We now turn to a discussion of these results in light of the two assumptions concerning the origin of the gas described at the end of Section I. We consider first Model B in which it is assumed that the gas which now gives rise to the line spectra originated in the central continuum source. In this case it must co-exist with an extremely high density of cosmic-ray particles. Such continuum sources have dimensions of light years or less. Let us suppose that $\sim 10^{57}$ erg of protons with $\bar{E}=100$ MeV are present in a volume with a dimension of 0.1 light year. Thus $\varrho_p=2.5\;10^5\,\mathrm{erg\,cm^{-3}}$ and for a typical spallation cross section of 100 mb, the lifetime of a heavy nucleus against spallation would be about 10 days. The escape time of the gas from such a region must be very much longer than a year since the gas cannot be expelled at relativistic speeds, consequently the gas would be completely spalled, and the abundances would be those given by Equation (2), i.e. $n(A)\propto S_A A^{-2/3}$.

Now all of the abundance analyses of the emission-line spectra suggest that, with the possible exception of helium, the composition is normal. Thus, we conclude that, if the proton flux is present, this gas cannot have originated from the central continuum source, or else it has been shielded from contact with the particles generated in the center.

We now consider model A. In this case the mean radius of the gaseous region is R_G and the gas resides there for a time $T_G=R_G/U_G$. Energetic protons are injected into the volume $V=4/3\,\pi R_G^3$ at an average rate given by ε_p/τ where τ_e is the characteristic time for escape of the particle flux from the central continuum source. Once the protons have been injected into the gas we assume that they propagate by adiabatic deceleration and diffusion in the same way that cosmic-ray particles are thought to propagate in supernova remnants. By analogy with the supernova case, the effective residence time is given by $\tau_G=T_G=R_G/U_G$. The balance between injection and loss from these different processes will generate an average particle energy density,

$$\varrho_p=\frac{\tau_G}{\tau_e}\frac{\varepsilon_p}{V}$$

and

$$\varrho_pT_G=\frac{\tau_g^2}{\tau_e}\frac{\varepsilon_p}{V}=\frac{3\varepsilon_p}{4\pi\tau_eU_G^2R_G}.$$

Putting $\varrho_pT_G\leqq 4\;10^9\,\mathrm{erg\,s}$, $\tau_e=1$ year $\approx 3\;10^7\,\mathrm{s}$, $U_G=10^8\,\mathrm{cm\,s^{-1}}$, $R_G=30\,\mathrm{pc}\simeq 10^{20}\,\mathrm{cm}$, we find that

$$\varepsilon_p\leqq 4\;10^{53}\,\mathrm{erg}.$$

Thus for this example we conclude that $\varepsilon_p/\varepsilon_e\ll 1$, i.e. the flux of protons interacting with the gas is very much smaller than the flux of relativistic electrons which must be present to explain the continuum synchrotron source.

In these calculations we have neglected the effect of energy loss by ionization on the spallation yields. The following argument shows that for the numbers we have used this effect is small. The Bethe-Block equation (neglecting the logarithmic term) for the energy loss due to ionization of the ambient gas is given by:

$$-\frac{dE}{dt}=2\;10^{-13}\frac{n_Gf}{\beta}\,\mathrm{MeV\,s^{-1}},$$

where n_G is the number density of the ambient gas and f is the filling factor. For $n_G=10^6\,\mathrm{cm^{-3}}$, $f=10^{-4}$ and $\beta=\bar{\beta}=0.4$, $E=\bar{E}=100$ MeV, $-dE/dt=5\;10^{-11}$ MeV and $\tau_1=E/(dE/dt)=2\;10^{12}$ s.

To take ionization losses into account we should therefore replace the residence time τ_G used in the previous analysis by

$$\tau_{\mathrm{eff}}=\frac{\tau_G\tau_I}{(\tau_G+\tau_I)}.$$

From the previous discussion we see that $\tau_G=10^{12}$ s. Thus $\tau_{\mathrm{eff}}=2/3\,\tau_G$, so that spallation will be reduced by about 30% by the effect of ionization loss at $E=100$ MeV. However, the particles are likely to have a spectrum of the form $N(E)\propto E^{-\gamma}$, and with increasing energy of the particles the ionization losses become progressively less important.

The result obtained in the example given here, that the total energy of the proton flux interacting with the gas could only be a small fraction $\lesssim 10^{-4}$ of the energy in the relativistic electron flux, clearly depends on many uncertain parameters. For example, if the high-energy protons were able to propagate through the gas in a time short compared with the time given by the diffusion approximation, fewer spallations would result, and a larger flux of particles would be compatible with the limit on the boron abundance. Even with the timescales used, much depends on the details of propagation. For example, we have made no mention of the magnetic fields which constrain the particles, since we have no knowledge of the magnetic configuration in the line-producing regions. We know that the gas is condensed into filaments or shells and that the filling factor is $\sim 10^{-4}$. In the unlikely event that the magnetic fields in the filaments are closed, the particles may largely avoid these dense regions and thus give rise to little spallation. On the other hand, it is more likely that the particles will reside for a large fraction of the time in the higher density regions in filaments, thus encountering more gas and giving rise to more spallation. Our best guess is therefore that the limits placed on the flux of protons interacting with the gas are still very conservative, so that the actual flux limit might be still lower than the value estimated earlier.

V. Conclusion

We have shown that by looking for evidence for spallation products in the spectra of QSO's, important conclusions can be drawn concerning the interaction of the high-energy particle flux with the gas. Further spectroscopic investigations with high resolution and more work on models for the emitting and absorbing regions, may lead to an improvement in the upper limits to the boron abundance, and hence to the flux of high-energy protons which has interacted with the gas.

At present there is no evidence that the emitting or absorbing gas has interacted in any significant way with a nucleon flux to produce boron. This does not necessarily set a very severe limit to the presence of a nucleon flux provided that it is of sufficiently low energy ($\lesssim 30$ MeV/nucleon), below the threshold for boron production. However, since the radio observations certainly suggest that relativistic electrons are present, it would be surprising if a large flux of protons with energies $\gtrsim 100$ MeV was not also present.

It is also clear that the gas seen in emission and absorption cannot have originated in the central continuum source, since if it has been ejected in the explosive events that give rise to the large fluxes of particles, not only would it have been subjected to intense particle irradiation, and its composition would have been drastically altered, but it almost certainly would be a mix of nucleosynthesis processes from the final evolution of normal and/or massive stars so that its composition would be highly abnormal.

The most likely source of gas of normal composition is that it has been ejected from stars in the course of the normal processes of stellar evolution. It might then be argued that the gas in the very central region which is heavily spalled is either swallowed up by a hypothetical massive black hole, or else it is largely diluted by much more gas arising in a greater volume with a radius corresponding to the size of the emission-line region. The gas in this latter volume does not interact appreciably with the proton flux.

Another point of some interest is that, while in some QSO's there is evidence of the generation and expansion of the colossal fluxes of relativistic electrons over timescales of years or less, there has never been any evidence that they have disturbed or given rise to changes in the emission-line regions, though the energies are so high that it is reasonable to suppose that the gas could easily be driven completely away (Jones and Burbidge, 1973).

A plausible model which can account for the result obtained in this paper and also the null effect mentioned above is one in which the particle ejection takes place axisymmetrically and is confined to a small solid angle. This is to be expected on the basis of both large and small radio source configurations. If it is then argued that the gas originating some distance ($\geqq 1$ pc) from the exciting center is distributed roughly spherically symmetrically initially, but the first blast of particles blows holes in equal and opposite directions and since we know from the radio observations that the same configuration persists (the source has a memory) successive particle bursts will not interact with the gas. Thus, there is no effective particle driving of the gas, the only effective force being the radiation driving which has been extensively investigated elsewhere.

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