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A PLAUSIBLE ENERGY SOURCE AND STRUCTURE FOR QUASI-STELLAR OBJECTS

by

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Abstract

If a collision of two large, massive, fast gas clouds occurs, their kinetic energy is converted to radiation in a pair of shock fronts at their interface. The resulting structure is described and the relevance of this as a radiation source for QSO's is considered.

1. The Mechanism.

A very simple solution to the long standing problem of the QSO energy source may exist in a mechanism being considered by Osterbrock (see, for instance, Osterbrock, 1971) for active galactic nuclei, including those of Seyfert galaxies. This process involves the conversion of large scale kinetic energy to electromagnetic radiation at or near a pair of shock fronts between dense colliding gas clouds. In this section we explore the basic constraints which are imposed on such a model by observations of QSO's.

As material flows into a shock front, its energy is first thermalized and, if time permits, is radiated. As a consequence, the total luminosity of a pair of such fronts between clouds of cross-sectional area A is

$$\mathcal{L} \simeq 2A \times (mv_o^2/2) \times n_o v_o$$

where n_o is the number density in the clouds and v_o is the shock velocity (1/2 of the relative velocity of the clouds).

In the case of a QSO, the shock velocity is limited by the observed line widths (see, for instance, Burbidge (1967) for a review of QSO properties) to be generally about 1000 km/sec, implying from $5kT = mv_o^2/2$ (m = average mass of the nuclei) that the post shock temperature is roughly 1.5×10^7 °K, taking the helium abundance to be about 10% by number. In addition fluctuations on a time scale of order one year require that the cooling time behind the shock be about 1 year, assuming that the luminosity fluctuations simply mirror fluctuations in the density of material entering the shock front. The cooling time is given by 5kT/Ln, where L is the cooling coefficient (in ergs cm^3/sec). If bremsstrahlung accounts for most of the cooling (Cox and Daltabuit, 1971) then $t_c \sim 0.1\ v_o/n_o$ years. Therefore we require $n_o \simeq 10^7$ particles/cm^3. The total radiation flux is then approximately $\rho_0 v_0^3/2 \simeq 10^7$ ergs/cm^2 sec, or 1 watt/cm^2, which is similar to a low wattage light bulb.

If this mechanism is to be the QSO energy source we clearly require a very large shock area. For example 10^{45} ergs/sec are generated by a shock area of 10^{38} cm^2. The radius of the smaller cloud involved in the collision must then be about 1.3 pc. The mass of such a cloud is 2.5×10^6 $M_\odot$, similar to a large globular cluster. It should be noticed that this collision would last only for a time $2r/v_0$ or 2400 years, implying that the state of being a QSO is ephemeral or repetitive.

Of course it must be shown that such an energy converter produces the correct spectrum, and that the physical conditions which would produce the collision are achievable. These points are discussed briefly in the subsequent sections.

II. Structure and Spectrum.

A. Shock Fronts and Cooling Regions.

As the two clouds come together, the gas of each enters a shock front where its kinetic energy is thermalized, its density raised to $4n_0$ and its velocity reduced to $v_0/4$. These are standard results for high velocity shock waves (see, for instance, Zel'dovich and Raizer, 1967). Behind each shock there is a cooling region with nearly constant pressure from which most of the thermal energy is radiated as the gas flows through. The width of this region is approximately equal to the cooling time t_c multiplied by the flow velocity $v_0/4$, or

$$d_c = 7.5 \times 10^5 \; v_0^2/n_0 \text{ cm } (= 7.5 \times 10^{14} \text{ cm})$$

where the number in parentheses corresponds to $v_0 = 10^8$ cm/sec and $n_0 = 10^7$ cm^{-3}.

This shock and cooling region effectively converts the entire kinetic energy of the entering gas to electromagnetic radiation.

B. HII Regions.

Most of the radiation from the cooling regions, however, is beyond the Lyman limit and as it propagates either upstream into the clouds, or downstream into the already cold dense gas flowing out of the cooling regions it is strongly absorbed to form HII regions, one leading and one trailing each shock. These two HII regions process nearly equal amounts of the ionizing radiation, but they differ in size and secondary spectrum because of their extreme difference in density. The leading HII region has a density of 10^7 cm^{-3}. The trailing HII region has a pressure $\rho_o v_o^2$, implying a density of 10^{11} cm^{-3} if its temperature is 10^4°K, or in general $10^{15}/T_d$ cm^{-3}, where T_d is the local temperature. (This value of the density depends on the contribution of magnetic fields to the pressure, which has been neglected here.)

Again assuming bremsstrahlung to be the dominant cooling mechanism in the cooling regions, the average number of ionizing photons which must be processed by the HII regions is approximately 5 E_1 $(I_H/kT) \simeq 20$ for every atom entering the shock front. In either HII region the density is so high that its thickness is quite small, about 3 x 10^{14} cm for the leading region and perhaps 4 x 10^6 cm for the trailing region, so that all the emitted radiation is converted to photons with $h\nu \leq 13.6$ ev in a pair of thin sheets sandwiching the narrow cooling region. Even the bremsstrahlung X-rays are absorbed within a very short distance in the clouds (which are neutral because of the very short recombination time for hydrogen).

C. Anticipated Spectrum.

Both the cooling and the HII regions have considerable temperature and ionization structure. The HII regions are expected to be similar to those considered by Mac Alpine (1972) and Davidson (1972), except for the low radiation density in the primary source considered here. The emission lines will thus originate from a wide range of ionization stages. Some of the most intense lines expected from the cooling and HII regions are shown in Table 1. Since the gas behind the shock slows down as it cools, coming essentially to rest with respect to the clouds, the lines observed will have widths up to 1000 km/sec, corresponding to the velocity separation between the emitting regions. In the denser region behind the shock collisional quenching can be expected for some lines. These lines will thus suffer only the thermal broadening that occurs in the leading HII region. The spectrum will then consist of a mixture of broad and narrow lines similar to that described by Burbidge (1971).

There is a very dense sheet of material between the two shock fronts. This consists of material which has passed completely through one or the other of the shocks, and its associated cooling and HII regions. As has been mentioned the density in this sheet, in the absence of magnetic fields, would be $10^{15}/T_d$ cm^{-3}, and the sheet thickness would be about 4×10^{10} T_d cm when the collision is half over. If sufficient dust is present in this region it may be expected that the radiation reaching it will be absorbed by molecules and dust, and be re-radiated as characteristic or black-body radiation. If so, the effective temperature would be a few hundred degrees.

D. Opacity of the Neutral Clouds.

The column density of neutral hydrogen in one of these clouds is about 4×10^{25} cm^{-2}. To prevent the entire luminosity of this object from escaping only in the infrared, it is required that the dust to gas ratio in the clouds, which surround the emitting regions, be 10^4 - 10^5 times smaller than in the interstellar medium in our galaxy. If the clouds are assumed to have 10 times less heavy element abundance, similar to population II stars, the dust to heavy element ratio need only be 10^3 - 10^4 times smaller than in our galaxy. On the other hand, if the interior cold dense region is to be thick enough to provide characteristic or thermal infrared radiation, the dust to gas ratio there should be slightly higher. This may be a reasonable consequence of the material's density and thermal history, i.e., the baking which this gas undergoes in passing through the interior HII region could have stimulated molecule and dust formation. We have not pursued this idea numerically.

The flux of non hydrogen-ionizing radiation produced in the cooling region and in both HII regions is sufficient to ionize all the heavy elements with ionization energy below that of hydrogen, and to do so without diminishing appreciably. This flux is also more than sufficient to ionize all the H^- that forms in the clouds. This means that the bound-free opacity from both heavy elements and H^- is negligible. The electrons existing in the cloud have such low abundance, and the HII region is so thin, that electron scattering is of no consequence. The free-free opacities both from H^- and the heavy elements only become important in the far infrared or beyond because of the low electron abundance.

A substantial fraction of the energy emitted in the HII regions, and to a lesser extent, in the cooling region (Cox and Tucker, 1969) will appear in the form of Ly α radiation. The cloud is indeed thick at this wavelength. However, the Ly α produced in the cooling region and in the trailing HII region is emitted far in the wings of the absorption profile of the unshocked portion of the cloud. This radiation will diffuse both in space and in frequency (Osterbrock, 1967) and part of it will eventually escape. The number of scatterings required for escape, however, is so large that the probability of conversion to 2 photon Ly α continuum (or to other lines by collisional quenching of this continuum) is substantial. This could contribute to the continuum spectrum of this object. The Ly α emitted in the leading HII region is emitted in the core of the absorption profile, and is all converted. All the Ly α that enters the unshocked portion of the cloud effectively populates the n = 2 level of hydrogen, and this population could be enough to make the Balmer continuum opacity marginally significant.

The transfer of radiation through the cloud is not a trivial problem, and its solution requires a knowledge of the spectrum of the cooling and HII regions. This latter problem is being studied at present. It seems, however, that in the absence of dust, the clouds are fairly transparent, and that most of the radiation will emerge almost as emitted by the HII regions.

III. Origin

This energy source requires the collision of two clouds of mass $\sim 10^6$ $M_\odot$, and size ~ 1 pc, traveling at velocities of 10^8 cm/sec. If gravitation is the source of acceleration, the total mass M_t required is given by $v^2 \simeq GM_t/R$, where R is the maximum size of the object containing the clouds. We have then (with $v_8 = v \times 10^{-8}$)

$$v_8^2 \simeq 4.4\ (M_t/10^{12}\ M_\odot)/R_{kpc}\ .$$

If R = 1 kpc, for example, $M_t \simeq 10^{11}\ M_\odot$.

The Jeans' length for the clouds we consider is

$$\lambda_t = 2.1 \times 10^{-2}\ \text{pc}\ (T_2/n_7)^{1/2}$$

The clouds will therefore collapse, and the free fall time is

$$t_{ff} \simeq 1.5 \times 10^4\ n_7\ \text{years.}$$

The pressure-free calculation is appropriate because the transparency of the clouds keeps the temperature from rising (see, for instance, Mestel, 1965).

The short lifetime of such clouds seems to indicate that in order to make a collision probable, a number of such clouds must exist within a fixed volume. By requiring that the time between collisions be of the order of the duration of one collision we obtain the condition

$$N^2 = (4/3)\ (R/r)^3$$

where N is the number of clouds of radius r contained within a radius R. If R = 1 kpc, N = 4×10^4 and most of the mass required is contained in the form of clouds. For smaller values of R fewer clouds are allowed and a large central mass must supply the required velocities.

All this indicates that a possible location for the occurrence of collisions is in the early stages of galactic formation. Consider an initial mass of $10^{12}\ M_\odot$, with a radius of 100 kpc and a temperature of 10°K. Within it assume density fluctuations with $\delta\rho/\rho = 10^{-3}$, radius of 1 kpc and mass $10^6\ M_\odot$. After a time t = 5×10^8 years the condensations will be similar to the clouds we have discussed, while the whole object will be about 1 kpc in radius and will have a mean density of $10^4\ cm^{-3}$. All this has been calculated using only the simplest arguments of non-rotating, spherical, pressure-free collapse (see, for instance, Mestel, 1965).

In any case, it seems very likely that the collision of two massive, large, dense, fast clouds might occur during the early stages of galactic formation, as discussed, for instance, by Mestel (1965) or Brosche (1970). The short lifetime of the clouds and the comparable duration of the collision indicate that very few collisions will occur in one object. The remnants of such collisions will be sheets of high density where rapid star formation may occur. Also, magnetic fields might be compressed in such sheets, and if illuminated with bursts of high energy electrons from nearby supernovae explosions might provide the environment for Kellerman's model of the radio sources (Kellerman, 1966). Another possibility is that the compression and therefore enhancement of the B field by the shock and subsequent cooling, and the compression of any ambient cosmic ray electrons (which results in enhanced electron energies) could alone provide the radio emission. If the primordial B field were somewhat uniform even the dipolar structure might be expected. One very nice feature of this model is that the energy available in the original cloud motion amounts to about 4×10^{54} ergs. The energies required do not then seem too overwhelming.

IV. Conclusions.

If two clouds with the appropriate characteristics collide with relative velocity of about 2000 km/sec, their kinetic energies are transformed 3 times before an observable spectrum is produced. The kinetic energy is first gradually thermalized as the cloud flows into a standing shock front. The thermal energy is then radiated by the cooling region as high energy photons. These photons are absorbed and the energy re-radiated by the HII regions. A fraction of the HII region radiation is lost as it flows out of the object to the opacity of the neutral clouds. The spectrum which is then observable is expected to be rather similar to those calculated by Mac Alpine (1972) and Davidson (1972) [see Mac Alpine (1971) for preliminary results]. Our results suggest that such collisions could be expected in the normal process of galaxy formation, making QSO's rather unexceptional objects. Our discussion in no way requires this; however, it is a straightforward way of getting the required cloud kinetic energies.

In closing it should be noticed that there are some superficial and some not so superficial resemblances between the model described here and conclusions reached by Davidson (1972). The cloud-cloud collisions described by Davidson were used only to provide regions of differing density. The radiation produced by the shock waves during the collisions was ignored in favor of an external unspecified UV source with a power law spectrum. Since we propose a specific energy source, whose spectrum can be computed, we feel that this work is complementary to that of Mac Alpine and Davidson. As previously mentioned, we are now working to produce a reliable spectrum of a 1000 km/sec shock wave and cooling region which we then expect to use with the photoionization program of Mac Alpine (1972) to find the ultimate spectral results of our model.

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Table 1

Strongest Lines That May Appear in the Spectra of the Emitting Regions (Not Including H and He Lines)

Cooling Region (1)	λ(Å)	HII Region (2)	λ(Å)
CII	1334	CIII]	1909
CII]	2326	CIV	1550
CIII]	1909	NV	1239-1243
CIV	1550	[OIII]	5007-4363
NV	1239-1243	OIV]	1406
OIV]	1406	OVI	1033
OV]	1213	NIV]	1488
OVI	1033	[NeIII]	3869
MgII	2748	[NeV]	3426
SiII	1824	MgII	2798

(1) Preliminary results of a calculation of the spectrum of the cooling region.

(2) Estimated from the results of Mac Alpine (1971, 1972).

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