ANNIHILATION MODEL OF QUASI-STELLAR OBJECTS

HANNES ALFVÉN

Dept of Applied Physics and Information Science, University of California at San Diego, La Jolla, California, U.S.A.

(Received 28 February, 1979)

Abstract. The possibility that annihilation is a major source of energy in cosmic physics is discussed. Since Klein suggested that the Universe might be matter–antimatter symmetric over two decades ago, there have been a significant number of papers developing the consequences of this view. These, however, have been largely ignored in the general literature. There have also been a number of papers claiming to prove that there cannot be antimatter anywhere in the observable Universe. In the first part of this paper an assessment of the differing views is given, and it is shown that none of the arguments against antimatter is convincing. The existence of antimatter is not in conflict with any observational fact. The reason for the negative attitude towards the existence of antimatter seems to be that this view is in conflict with a number of speculative but 'generally accepted' theories. However, recent magnetospheric and heliospheric research, including *in situ* measurements of cosmic plasmas, is now drastically changing cosmic plasma physics in a way that leads to growing scepticism about quite a few of the speculative theories.

An attempt is made to develop a simple phenomenological model of QSOs based on star–antistar collisions. This model can account for such basic observational properties as the acceleration to very large (non-cosmological) velocities, the existence of broad emission lines, and at the same time narrow absorption lines with different redshifts. The absence of blueshifts is also explained. The model predicts that relatively young QSOs should be at cosmological distances whereas the old ones may very well be much closer to us than indicated by their redshift.

1. Annihilation as a Source of Energy

1.1. Existence of Antimatter

During the last decade a number of celestial objects have been discovered in which the release of energy is too large to be accounted for by nuclear reactions. Without introducing new laws of physics there are only two possible sources of energy: annihilation and gravitational energy. Quite a few theories have been proposed in which annihilation is supposed to deliver the energy (see, for example, Alfvén, 1965, 1971, 1977a, b; Elvius, 1969; and Omnés, 1969) but in the recent discussion the interest is so completely focused on gravitation as a source of energy that the annihilation theories are seldom mentioned. The extent to which the annihilation taboo is rationally motivated seems to be due to a number of misunderstandings. In reality, although the existence of antimatter is in conflict with several speculative but generally accepted theories, it is not in obvious conflict with any observational fact (Alfvén, 1977a, b). The following points should be remembered:

Astrophysics and Space Science **64** (1979) 401–419. 0004–640X/79/0642–0401$02.85

1.2. Similarity of electromagnetic radiations from the two kinds of matter

The kind of matter of which a celestial body consists cannot be decided by a study of the electromagnetic radiation it emits. The sign of some magnetic effects (circular Zeeman effect and Faraday rotation) depend not only on the kind of matter but also on the sign of the magnetic field; and because there is no independent way of measuring the sign of the magnetic field, no conclusions can be drawn about the kind of matter.

1.3. Radiations from annihilation processes

Mixing of the two kinds of matter produces *neutrinos, γ-rays, and relativistic electrons–positrons.* It has been claimed that if large quantities of antimatter exist in the Universe such radiations must be above the measured levels (Steigman, 1976a, b). This conclusion is not correct (Thompson and Rogers, 1979). Certainly if we accept the usual picture of interstellar space as filled with a rather homogeneous plasma in turbulent motion, we can exclude the existence of appreciable quantities of antimatter in our Galaxy. However, recent magnetospheric–heliospheric observations compel us to change this view in a drastic way (Fälthammar *et al.*, 1978).

1.4. Cellular structure of space

A number of interfaces have been discovered which separate regions of different magnetization, density, temperature, electron velocity distribution and even chemical composition. Examples are: the magnetopause and magnetotail sheets, the heliospheric equatorial sheet (earlier erroneously referred to as 'sector structure') and similar sheets in the Jovian magnetosphere and possibly also in the cometary tails.

These sheets are caused by electric surface currents (Alfvén, 1977a, b). They are sometimes very thin (down to a few times the ion Larmour radius), and it is almost impossible to detect them from a distance. A spacecraft usually sees no indications of such a sheet until it actually passes it.

As it is unlikely that cosmic plasmas have such properties only in those regions which are accessible to spacecraft diagnostics, it is legitimate to conclude that *space in general has a 'cellular structure'*, although this is almost impossible to observe unless a spacecraft penetrates the 'cell walls' (current sheets). A revision of our concept of the properties of interstellar (and intergalactic) space is an inevitable constituent in the thorough revision of the theory of astrophysical plasmas which necessarily will follow from recent magnetospheric discoveries (Fälthammar *et al.*, 1978).

The new picture of the properties of space voids the objections against the existence of antimatter within our Galaxy. We are not in conflict with any observational facts if we assume that there are cells containing antimatter adjacent to cells with koinomatter and separated from these by Leidenfrost layers. In two papers Lehnert (1977, 1978) has studied such layers theoretically (Figure 1). In his first paper he assumes a homogeneous magnetic field parallel to the interface; in the second, a combination between a Leidenfrost layer and a current sheet of the type observed in the magneto-

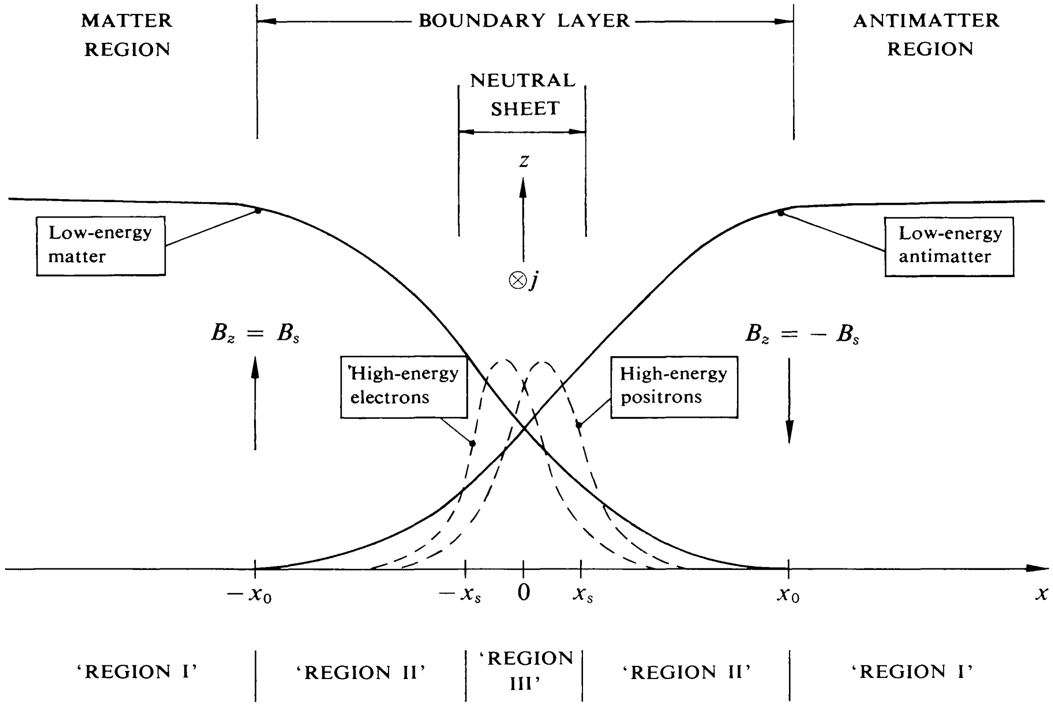

Fig. 1. Schematic density profile in a boundary layer separating matter from antimatter in the case of a fully ionized plasma confined in a magnetic field B. The latter reverses direction at the plane $x = 0$, on account of a current j flowing in the y direction within a magnetic neutral sheet. Matter and antimatter diffuse from each side of the regions $x \ll 0$ and $x \gg 0$ towards the central plane $x = 0$ to compensate for the loss of particles due to annihilation in the layer defined by $-x_0 < x < x_0$. The neutral sheet region, defined by $-x_s < x < x_s$, forms an inner part of the boundary layer (from Lehnert, 1978).

pause. As we know from observations that the current sheets in the magnetosphere–heliosphere have a high degree of stability, we can expect that even when combined with a Leidenfrost layer it should be stable. As an example, suppose the solar wind consisted of antimatter. When reaching the magnetopause, it would be deflected in the same way as the present solar wind and very little antimatter would penetrate through the magnetopause.

1.5. Annihilation in cosmic clouds

If the Universe is symmetric with regard to koinomatter–antimatter, or if there exists a considerable quantity of antimatter, there are a number of situations in which annihilation may be important.

The first case we should consider is an encounter between cosmic clouds of opposite matter.

Annihilation processes produce a repulsion between the clouds and, according to recent investigations by Thompson and Rogers (1979), lead to an establishment of more or less stationary Leidenfrost layers of essentially the types studied by Lehnert.

The total radiation from such a layer is calculated and only in extraordinary circumstances should it lead to the emission of a measurable quantity of γ-rays.

1.6. Bodies falling into a star of opposite kind of matter

Our second example referes to the fall of a small body (e.g., of the size of an asteroid or a cometary nucleus, typically 10^{19} g) into a star. When the solid body hits the photosphere of the star, a burnout takes place in a few minutes. This seems to account for the X-ray burst (Sofia and van Horn, 1974; Vincent, 1976). The time constants of the rapid variations as well as the total emitted energy are of the expected order of magnitude, and the frequency of the events is reconcilable with the expected collision frequency.

The size spectrum of most groups of celestial bodies shows a rapid increase in number with decreasing size (see, e.g., Dohnani, 1976). Hence, we should expect a large number of very small γ-ray bursts. Such bursts have actually been observed, mainly from balloons (see, for example, White *et al.*, 1978).

Going to larger bodies we should remember that in the solar system there are supposed to be 10^{11} comets and 10^4 observable asteroids, but the number of bodies of the size of satellites and planets is much smaller. If we take this distribution as representative of the size distribution of bodies in our Galaxy with which a randomly moving star is likely to collide, we should expect that with increasing mass of the impacting body the number of events should decrease rapidly. At the same time the quantity of emitted γ-rays should increase so that the γ-ray bursts become more conspicuous. However, already in the ordinary γ-ray burst the γ-ray emission is limited by absorption in the gas cloud produced by the evaporation of the small body (Thompson, 1978), and most of the observed γ-rays are due to secondary processes in this cloud. As the size of the evaporated cloud will increase with the size of the impacting body and, moreover, the burnup will be retarded so that ultimately it takes place under a cover of massive layers of the upper photosphere, there will be a saturation in the increase in size of the γ-ray burst (cf. Figure 2).

The relativistic e^+e^- gas which also is produced by annihilation is not subject to the same saturation. In fact – as will be discussed in detail later – it is likely to be emitted, even from large depths, in the form of jets or bubbles, which expand in the surroundings of the celestial body. In the presence of magnetic fields this component will emit synchrotron radiation, detectable at radio wavelengths and perhaps also much shorter wavelengths. Hence we should expect that the γ-ray burst should be accompanied by radio bursts, and also that there should be similar much larger radio bursts but with a much smaller frequency.

The neutrinos, of course, cannot be appreciably absorbed but as our recorders are not sensitive enough we cannot get any information from them (Thompson and Rogers, 1979).

In Section 2 we shall treat two cases of collisions between condensed bodies: when

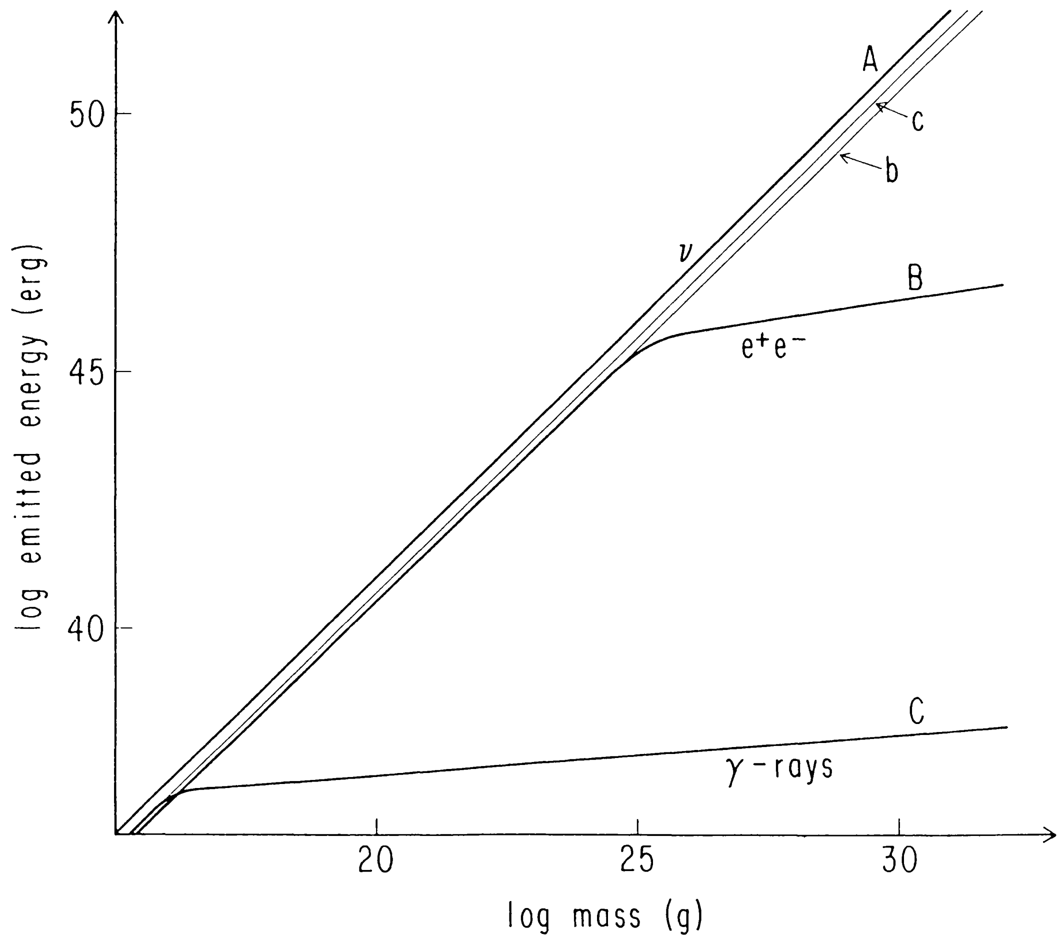

Fig. 2. Energy emission W when a condensed body with mass m annihilates in stars. Curve (A): $W = mc^2$. Neutrino energy and also total non-neutrino energy. Represents upper limit to total electromagnetic radiation (including light) from ambistar. (b) $W = \frac{1}{3}mc^2$. Energy released as e^+e^- relativistic gas. (B) Most of the e^+e^- is emitted but self-annihilation gives saturation at $M \sim 10^{25}$ g (see Section 2.2). The curve gives the upper limit to emitted synchrotron radiation and also to the contribution to the continuous X-ray background radiation. (c) $W = \frac{2}{3}mc^2$. Energy released as γ-rays. (C) Because of absorption in the condensed body and the cloud produced when it evaporates, the emitted γ-radiation saturates, in part already when $m \sim 10^5$ g (see Section 1.6).

a star of solar dimensions is hit by a 'medium size' body, say of terrestrial mass, and when the impacting body is of stellar mass.

1.7. Continuous X-ray background radiation

The relativistic e^+e^- gas which is emitted in these events (and also in those to be discussed in Section 2) will expand out in space and will eventually fill intergalactic space. As shown by Carlqvist and Laurent (1976a, b), it should be possible to observe the gas there because starlight shining on it will produce X-rays due to the inverse Compton effect. In this way they explain the observed continuous X-ray background radiation without any *ad hoc* assumptions. The theoretical spectrum agrees well with the observed spectrum, and the intensity is of an acceptable order of magnitude.

Objections to this interpretation have been raised by Steigman (1976a, b), but Carlqvist and Laurent (1976b) have demonstrated that they are not valid (see also Thompson and Rogers, 1979).

2. Model of a Star Containing Both Kinds of Matter

In order to initiate a discussion on the possible properties of annihilation as a source of energy for QSOs we shall discuss two simple models called Ambistar Model I and Ambistar Model II. As our aim is only to get a general qualitative picture, we shall confine ourselves to the case when a star of solar dimensions is hit by a body of an opposite kind of matter which may be much smaller (Model I) or of comparable size (Model II). Outlines of these models have already been discussed in an earlier paper (Alfvén, 1978). The observational results which we use for comparison are mostly taken from Burbidge *et al.* (1974) and a number of papers in *Physica Scripta 17*, No. 3 (Burbidge and Burbidge, 1978).

2.1. Ambistar Model I

We assume that a star is impacted by a body of the opposite kind of matter which is much smaller but still large enough not to burn up immediately (which probably means $\gg 10^{20}$ g). After a very violent but brief initial phase (order of minutes) the matter of the impacting body will be a part of a composite star ('ambistar') containing both kinds of matter separated by a Leidenfrost layer. After a transient period (probably less than 100 years) the flow of energy inside the ambistar may reach a quasi-stationary state. In the separating layer, annihilation will produce neutrinos, γ-rays, and a relativistic e^+e^- gas. Because of the high temperature this region is likely to stay at the surface of the ambistar. We shall discuss a highly simplified model of the situation which is likely to occur.

We represent the photosphere of the ambistar by a plane $a'a''$ (see Figure 3). The matter M_1 originating from the infalling body is supposed to be confined inside a circular cylinder with radius R_c and height h_c. It is separated from the rest of the star M_2 by a circular Leidenfrost layer P called the production region where all the annihilation is supposed to take place, and the cylindrical shell with thickness Δ which we shall call the *exhaust channel E*. We neglect the annihilation which takes place in this.

We introduce the following notations:

The *gravitational pressure* at P is

$$p_g = \int_0^h \varrho g \, \mathrm{d}z, \tag{1}$$

with ϱ the density, g the gravitational force, and z the distance below the surface.

The *gas pressure* p_r of the relativistic e^+e^- gas, which has an average energy eV_a ($=0.5 \times 10^8$ eV $= 10^{-4}$ erg) and density n, is

$$p_r = neV_a. \tag{2}$$

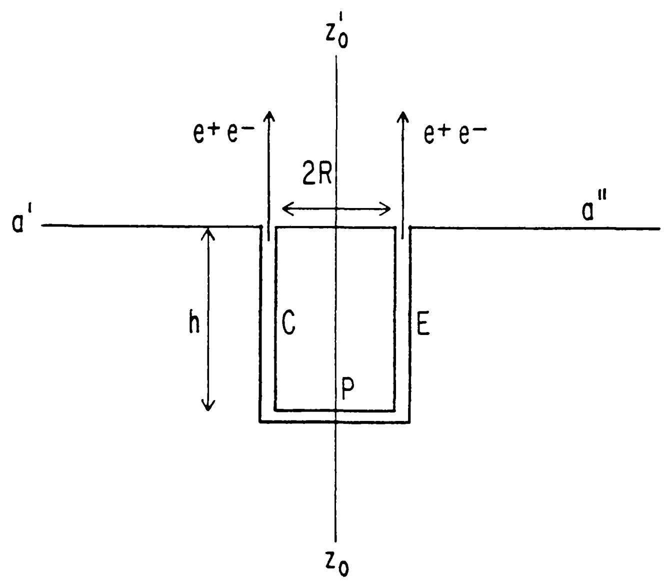

Fig. 3. Ambistar Model I. Near the surface $a'a''$ of a star of one kind of matter there is a volume of matter of the opposite kind, limited by a circular surface P and a cylindrical surface C. The axis of symmetry is $z_0 z_0'$. The two kinds of matter are separated by Leidenfrost layers. A relativistic gas of e^+e^- (10^8 eV) is ejected, essentially perpendicular to the stellar surface. In case the height of the cylinder is so large that the mass density exceeds $\sim 10^2$ g cm^{-2}, most of the γ-rays are absorbed. The intense energy release makes the surface region near the cylinder very hot, causing a very strong emission of light.

The *rate of annihilation* is N_a s^{-1} over the surface πR^2. As one-sixth of the total annihilation energy goes into kinetic energy of e^+e^-, we have

$$N_a e V_a = -\frac{c^2}{6}\frac{\mathrm{d}M}{\mathrm{d}t} \qquad \text{or} \qquad N_a = -1.5 \times 10^{24}\frac{\mathrm{d}M}{\mathrm{d}t}, \tag{3}$$

where $\mathrm{d}M/\mathrm{d}t$ is the total mass loss (of half koinomatter and half antimatter).

The *thickness of the exhaust channel* is Δ; hence, the cross-section of the exhaust channel is $2\pi R\Delta$. As the relativistic gas streams out with a velocity close to c, the emitted number of e^+e^- is given by

$$N_e = 2\pi R \Delta c n \text{ s}^{-1}. \tag{4}$$

A stationary state requires $p_g = p_r$; $N_a = N_e$. The output power is

$$P = -c^2 \frac{\mathrm{d}M}{\mathrm{d}t} = 6N_e V_a = 12\pi c e V_a R \Delta n = 10^8 R \Delta n \tag{5}$$

or

$$P = 12\pi c R \Delta p_g = 10^{12} R \Delta p_g. \tag{6}$$

2.2. Limit to Density of e^+e^- Gas

A limit to the density n of the relativistic e^+e^- gas is set by annihilation (cross-section $= \sigma_a$). In fact, the mean free path

$$\lambda = (n\sigma_a)^{-1} \tag{7}$$

must exceed the path from the production region out to space. Seen from the reference system of the electrons, the path is shortened relativistically to $h' = h\gamma^{-1}$, with $\gamma = eV_a(m_e c^2)^{-1} \approx 100$, where m_e is the rest mass of an electron. Hence, with $\sigma_a = 10^{-24}$ cm^{-2}, the saturation limit is

$$n_{\max} = (\sigma_a h)^{-1}\gamma = 10^{26}\, h^{-1} \tag{8}$$

and

$$P_{\max} = 12\pi c \frac{(eV_a)^2}{m_e c^2 \sigma_a} \frac{R\Delta}{h}; \tag{9}$$

or, with the above values,

$$P_{\max} = 10^{34}\, R\Delta h^{-1}. \tag{10}$$

The pressure at the bottom is

$$p_{\max} = neV_a = 10^{22}\, h^{-1}. \tag{11}$$

If the average density in the cylinder is $\bar{\rho}$, its mass M and the gravitation is g, we have

$$Mg = \pi R^2 h\bar{\rho} g = \pi R^2 p_{\max}. \tag{12}$$

With $g = 3 \times 10^4$ cm s^{-2} we have $M = 10^{18} R^2 h^{-1}$. Putting $R = h$ we obtain

$$M = 10^{18}\, R. \tag{13}$$

With $R = 10^{10}$ cm we have $M = 10^{28}$ g, corresponding to $\bar{\varrho} = M(3/4\pi)R^{-3} = 0.25 \times 10^{-2}$ g cm^{-3}. Hence, we see that in our model the pressure of the relativistic gas will reach its upper limit for a mass comparable to that of the Earth. (See Figure 2, curve B.)

2.3. Energy release in model

An output of, for example, 10^{43} erg s^{-1} can be obtained with $R \sim h$ and $\Delta = 10^9$ cm. The theoretical calculation of Δ is very difficult. The thickness of the Leidenfrost layer should be given by the condition that the koinomatter and antimatter become mixed to such an extent as to give the required annihilation. This depends not only on the thickness Δ but also on the magnetic field and especially on perturbations due to instabilities. As always, the theoretical prediction of plasma instabilities is extremely difficult. At present the only conclusion we can draw is that there is nothing obviously wrong with the value $\Delta = 10^9$ cm.

The mode of burning we have discussed might be stretched to give one or two orders of magnitude more output (e.g., with $R = 10h$ and $\Delta = 10^{10}$ cm). A still larger annihilation – which ultimately means higher luminosity – is possible with other modes of burning, but the e^+e^- output will not be increased very much. Further, we may have outbreaks of turbulent plasma clouds producing very intense annihilation. Such a state may be associated with outbursts of γ-radiation.

2.4. Emission of γ-rays, light, and e^+e^-

Our model has the following properties:

(a) *Emission of γ-rays:* Very little (except a minute long γ-ray burst at the start).

(b) *Emission of light:* One-third of the annihilation energy. This amount goes primarily into γ-rays, but as the mass of the layer with thickness h is likely to be larger than 100 g cm^{-2}, this is completely absorbed and re-emitted as light from the stellar surface. The size of the strongly heated part of the surface may be a few times πR^2. The light pressure will give a force

$$f_l = \alpha' \frac{c}{3} \frac{\mathrm{d}M}{\mathrm{d}t} \tag{14}$$

opposite to the direction of the jet. Here α' is a numerical factor equal to 1 when all the light is emitted parallel to the jet. If it is emitted isotopically over a half-sphere, $\alpha' = 0.5$.

(c) *Emission of relativistic gas:* One-sixth of the annihilation energy (neglecting e^+e^- annihilation). If it is emitted perpendicular to the surface of the ambistar, it will exert a force

$$f_e = -\frac{c}{6} \frac{\mathrm{d}M}{\mathrm{d}t}; \tag{15}$$

so that the total force is given by the sum

$$f = f_l + f_e = \alpha c \frac{\mathrm{d}M}{\mathrm{d}t}, \tag{16}$$

with

$$\alpha = \tfrac{1}{6}(1 + 2\alpha'). \tag{17}$$

2.5. Acceleration of an ambistar

In order to begin with a case which can be treated in a simple way, we assume that no other force is active (cf. 2.9). In its own frame of reference the ambistar is accelerated $\mathrm{d}v/\mathrm{d}t = f/M$. We confine the discussion to the simple case when this acceleration is parallel to the original velocity u in relation to us. The change of velocity in our system then becomes

$$\mathrm{d}u = \left(1 - \frac{u^2}{c^2}\right) \mathrm{d}v. \tag{18}$$

This gives

$$\frac{\mathrm{d}M}{M} = -\frac{1}{\alpha} \frac{\mathrm{d}\beta}{1 - \beta^2}. \tag{19}$$

The initial mass of the star is supposed to be $M_a = M_1 + M_2$. After burnout the mass of the ambistar has decreased to $M_p = M_1 - M_2$. Integration gives

$$\log \left(\frac{M_a}{M_p}\right)^\alpha = \Delta\Phi \tag{20}$$

with $\Delta\Phi = \Phi_p - \Phi_a$, and

$$\Phi_a = \tfrac{1}{2}[\log(1 + \beta_a) - \log(1 - \beta_a)] = \log(z_a + 1), \tag{21}$$

$$\Phi_p = \tfrac{1}{2}[\log(1 + \beta_p) - \log(1 - \beta_p)] = \log(z_p + 1),$$

$$z = \frac{1 + \beta}{\sqrt{1 - \beta^2}} - 1 = \left(\frac{1 + \beta}{1 - \beta}\right)^{1/2} - 1 \qquad (= \Delta\lambda/\lambda). \tag{22}$$

The velocities before and after burnout are $\beta_a c$ and $\beta_P c$. In case the acceleration is antiparallel to the velocity we should introduce a minus sign in (20).

2.6. Emission of synchrotron radiation

When the e^+e^- gas escapes from the surface of the ambistar, it will emit synchrotron radiation with the frequency

$$\nu = \frac{1}{2\pi}\frac{eB}{m_e c}\gamma^2 = 3 \times 10^6 \gamma^2 B = 3 \times 10^{10}\, B \tag{23}$$

(with $\gamma = 100$). The wavelength is $\lambda = B^{-1}$ cm.

In order to obtain an emission of optical light ($\lambda = 10^{-4}$ cm) a magnetic field of 10^4 gauss is required. Stars with magnetic fields much in excess of that have been observed, and sunspot fields are almost of the same order of magnitude. As the very large release of energy may also cause an increase in the magnetic energy of the star, we cannot rule out an even higher magnetic field which means that even optical light can be emitted. However, the decay time of synchrotron emitting electrons is

$$T = 5 \times 10^8\, B^{-2}\gamma^{-1}. \tag{24}$$

Hence, even if they travel close to the velocity of light they will decay after having passed a distance

$$L = cT = 1.5 \times 10^{19}\, B^{-2}\gamma^{-1} = 1.5 \times 10^{17}\, B^{-2}\,\text{cm}. \tag{25}$$

With $\gamma = 10^2$, $B = 10^4$ we have $L = 1.5 \times 10^9$ cm (assuming the same magnetic field also below the surface); this means that h should not exceed $\sim 10^9$ cm. Hence, we conclude that synchrotron emission of optical light is possible, but only with the power limitation given by (9). Synchrotron emission in the far infrared (10–100 μ) is less severely limited.

The energy which can be emitted as synchrotron radiation cannot exceed one-sixth of mc^2, and is also limited by (10). The fraction of this that is actually emitted, and the wavelength region in which the emission takes place, depend upon the geometry and strength of the magnetic forces surrounding the ambistar.

The emission of synchrotron radiation will not necessarily be limited by selfabsorption because the electrons may bunch – a phenomenon well-known from magnetrons.

The continuous X-ray background. The emitted e^+e^- will eventually fill intergalactic space. As discussed in Section 1.7, the continuous X-ray background can be explained as the inverse Compton effect of starlight scattered by relativistic e^+e^-. The energy spectrum of the emitted e^+e^- is close to the primary annihilation spectrum only if n is well below the saturation limit (8), and the loss as synchrotron radiation is negligible. The observed energy spectrum of the X-ray background agrees well with the theoretically expected spectrum, except near the high energy limit.

2.7. Stellar collisions

We have now exhausted the list of properties which we can derive from Ambistar Model I. We shall proceed to the case when the impacting body is of stellar mass (comparable with the 'big' body).

We shall first discuss the moment of collision. In some respects the collision between two stars of opposite kinds of matter is similar to the collision between two stars of the same kind of matter. Because of its importance in the build-up of very massive stars – especially in galactic cores – this problem has attracted considerable interest and has been treated by Spitzer and Saslow (1966), Colgate (1967), Sanders (1970 and 1972), and Seidle and Cameron (1972) and others.

Depending on their models, the different authors reach somewhat conflicting results. It is obvious that the collision is highly inelastic and that there is an appreciable probability that two stars collide in such a way that they form a combined star with a mass which is not very much smaller than the sum of their masses. The combined star is greatly heated, so that the nuclear release of energy becomes much enhanced, and the star will oscillate violently. However, as the time of collision is very short ($\sim 10^3$ s) most of the oscillations will decay rather rapidly.

If two stars of opposite matter collide it seems reasonable that the very brief collision phase is similar. As annihilation is a surface phenomenon, primarily confined to a layer only a few mean free paths thick, the release of annihilation energy will not necessarily be large enough to affect the kinematics of the collision (in an analogy, to the release of nuclear energy).

2.8. Ambistar Model II

The situation that will be established after the transient effects have decayed is not very easy to calculate with any high degree of certainty. We shall make a model (Figure 4), necessarily speculative, based on the following two assumptions:

1. *We assume that the ambistar rotates and that the rotational axis coincides with the axis of symmetry in the matter–antimatter configuration* (cf. Section 2.1 and Figure 3). *This means that the direction of emission is spin stabilized.*

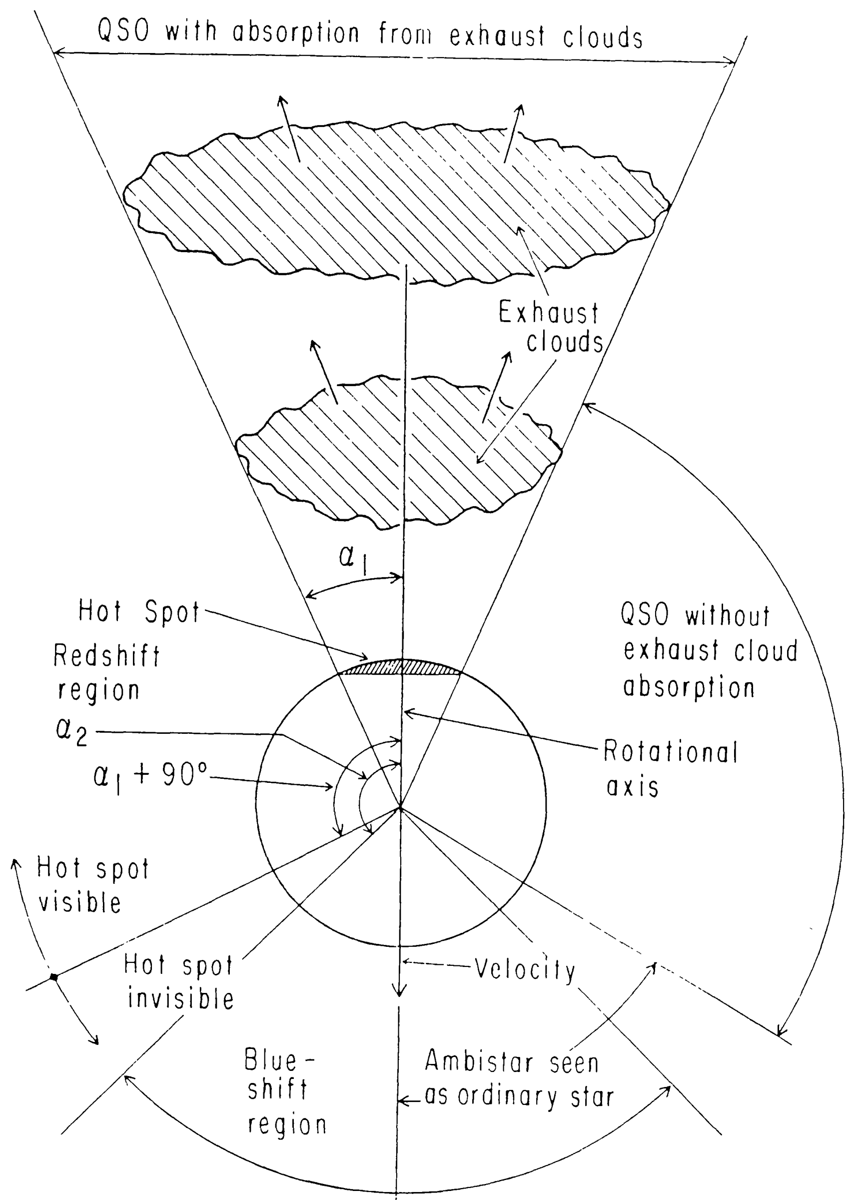

Fig. 4. Ambistar Model II. Observable properties of an ambistar depend on the angle α between observer and axis. If $\alpha < \alpha_1$, the ambistar is a QSO seen through the exhaust clouds which may cause several sets of *absorption lines*. In addition, there may be absorption in interstellar clouds for any value of α. The apparent luminosity depends on how much of the hot spot is visible (see Figure 5). The observable *redshift* is a function of α (see Figure 5). For $\alpha < \alpha_1 + 90°$, the ambistar looks like a QSO with redshift and for $\alpha > \alpha_2$, as an ordinary star with blueshift. If $\alpha_1 + 90° > \alpha_2$, there may be a narrow region where a faint blueshifted QSO may be observable.

It seems likely that this could be derived from a detailed analysis of the stability of an ambistar, but as the analysis may be difficult and has not yet been made, we must so far consider it as an assumption.

2. *We assume that the properties we have derived from Model I are essentially valid also for an encounter between two stars of comparable mass.*

Because the problem of the matter–antimatter configuration is very difficult – and as theoretical predictions in plasma physics always are precarious – this is the only thing we can do before a detailed ambistar model is worked out.

Ambistar Model I was derived under the simplifying assumption that the colliding stars have very different masses. However, acceleration of an ambistar to very high velocities requires that a large fraction of its mass is burned up, which means that the two stars of opposite matter must have masses which are not very different. Hence, the following conclusions can be drawn only under the condition that a generalized model can be worked out which gives similar results as our simple model. As z as a function of Φ is an exponential, very large z values are relatively easily reached.

As an example, $(z_p + 1)/(z_a + 1) = 2$ means $\Delta\Phi = 0.3$ and $(M_a/M_p)^\alpha = 2$. With $\alpha = 0.5$ or 0.25 this means $M_a/M_p = 4$ or 16, implying $M_1/M_2 = 3/5$ or 15/17.

2.9. Solar wind type emission

The excessive heating of a limited region of the ambistar surface is likely to cause a very intense 'solar wind' emitted radially from this region, the velocity of which we put equal to βc. Compared to the accelerating force resulting from light pressure and emission of relativistic e^+e^- gas, the solar wind recoil gives an increase in the force/energy ratio by a factor β^{-1} but a decrease in the force/(mass loss) ratio by a factor β. A solar wind emission may be of decisive importance for the evolution of an ambistar.

Of special importance is whether the emitted mass derives from the big body or the small body component. Our simple model cannot be expected to clarify such a 'second-order effect'. We have at least four options:

(a) Equal amounts of both kinds of matter are ejected.

(b) The emission consists essentially of matter from the small body.

(c) The emission consists essentially of matter from the big body.

(d) The state of emission oscillates more or less regularly between (b) and (c).

Handwaving arguments for any of these are easy to give, but – especially as predictions in plasma physics are usually precarious – the arguments are not very convincing.

Option (a) will give a violent mixing, resulting in annhilation reactions in the solar wind, but the end result may be similar to that of (d), viz., the formation of a number of clouds separated by Leidenfrost layers. Also, (b) and (c) will give rise to a number of discrete clouds, because – as we know from the present solar wind – fluctuations in emission velocity (which no doubt will occur) will produce bunching after some time (see Figure 4).

The crucial problem is whether most of the ejected mass comes from the small body or from the large body. In the first case the total acceleration is given by the original mass of the small body. If for a given acceleration of the ambistar its mass loss is larger than according to (16), the total acceleration before burnout will be smaller. On the other hand, if it is always the big body which supplies most of the mass loss, a complete burnout of the whole ambistar is possible, even in the case when the original mass ratio is rather far from unity. In this case the end of its life is characterized by $M \to 0$ and $z \to \infty$. This means that there may be QSOs with larger redshifts than have been observed so far.

Hence, we can see that there exists a possible mechanism for almost unlimited redshifts of QSOs, but it would not be fair to claim that we can derive this mechanism from the present models with any degree of certainty.

2.10 Observable properties of an ambistar

Our ambistar models are highly asymmetric, so that the observed properties depend on the angle α between the axis and the observer. We assume that the *light* which the observer receives is proportional to the projected surface of the hot spot (neglecting limb darkening) – see Figure 5. It is a maximum for $\alpha = 0°$, goes down to about 10% of this for $\alpha = 90°$ and to zero for $\alpha = 120°$. Hence, for $0 < \alpha < 90°$, and possibly also up to 120°, the ambistar will be identified as a typical QSO. For $\alpha > 120°$ the hot spot is invisible and hence the emitted light is down by several orders of magnitude. The ambistar, if seen at all, will appear as an ordinary star and not as a QSO.

The *radio emission* will also be asymmetric, but as part of it comes from e^+e^- when they are rather high above the surface of the ambistar, we should expect the shadow effect of the star to be less pronounced than for the light emission.

The observed *redshift* z_Q derives partly from the redshift z_q of the mother galaxy (which we assume to be 'cosmological') and partly from the relative velocity $\beta_A c$ of the ambistar in relation to the coordinate system of the galaxy which gives the redshift

$$z_A = \gamma_A(1 + \beta_A \cos \alpha), \tag{26}$$

with $\gamma_A = (1 - \beta_A^2)^{-1/2}$. (This redshift is the sum of the Doppler redshift and the transverse redshift.) If we assume z_g to be due to a motion antiparallel to the vector radius towards the observer, we have

$$1 + z_Q = (1 + z_g)(1 + z_A) \tag{27}$$

or

$$z_Q = C + D \cos \alpha, \tag{28}$$

with

$$C = z_g\gamma_A + \gamma_A - 1; \qquad D = (1 + z_g)\beta_A\gamma_A. \tag{29}$$

Figure 5 gives some examples of how z_Q varies with α. For $\alpha < 30°$ the redshifts are largest. In this domain the QSOs will be observed through the exhaust clouds and hence may show several sets of absorption lines with different redshift. For $30° < \alpha \gtrsim 120°$, the redshift of the QSO decreases rapidly with increasing α. The QSO is no longer seen through the exhaust gases but the light may still show absorption lines produced in ordinary interstellar clouds, which have essentially the same redshift as the mother galaxy.

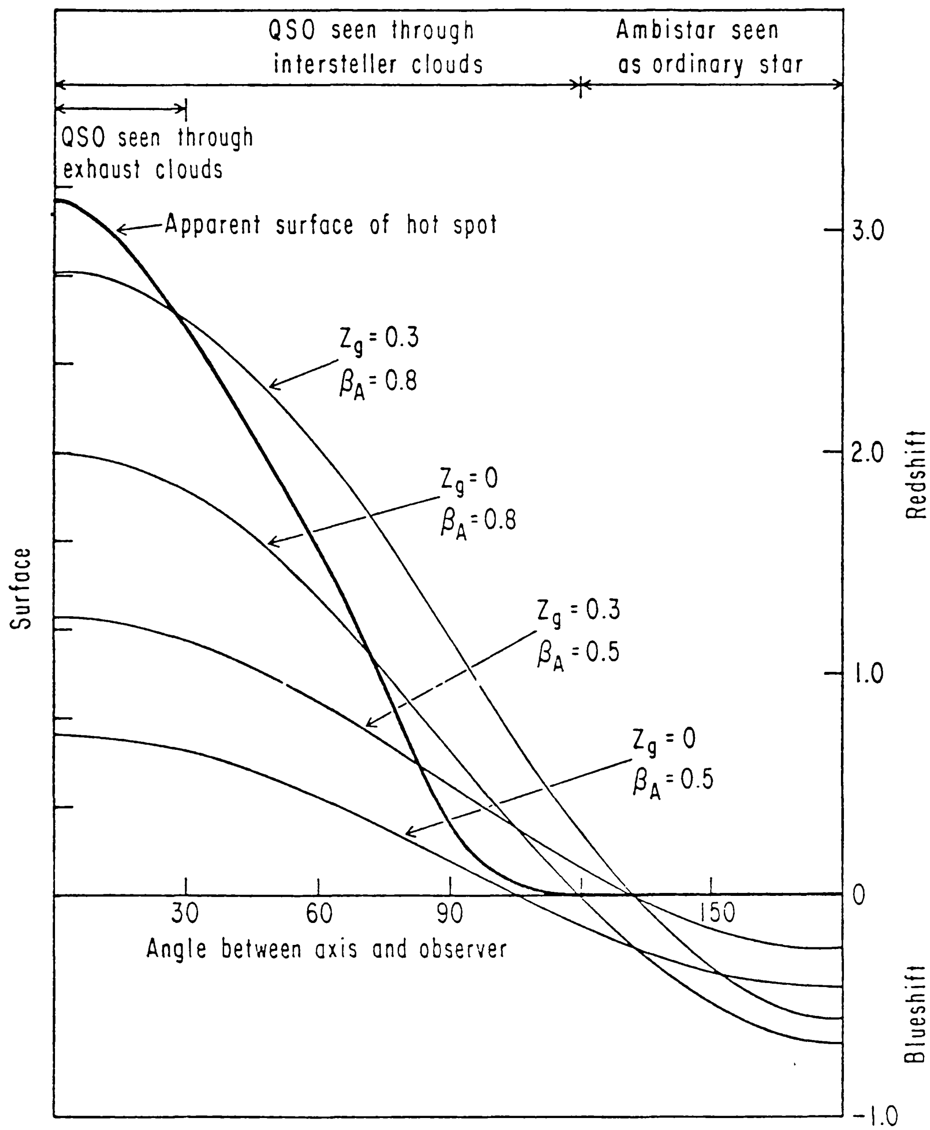

Fig. 5. Properties of ambistar as a function of the angle α between observer and axis. —— Apparent surface of the hot spot (assumed to be a measure of the luminosity). —— Redshift–blueshift from (28) of star moving with velocity β_A in relation to the mother galaxy which has the cosmological redshift z_g. The object is classified as a QSO only if the hot spot is observable, which means for $\alpha < 120°$. In our examples the QSOs are always redshifted (except for $z_g = 0$, $\beta_A = 0.5$, $105° < \alpha < 120°$ where blueshift is possible but the luminosity in this region is very small).

2.11. Blueshifts

When α exceeds the value given by $\cos \alpha = -C/D$ (which in our examples varies between 106° and 132°), its emission changes from redshift to blueshift. This takes place for $\alpha > 90°$ when the visible area of the hot spot is down to 10% or less, and often at $\alpha > 120°$ when the hot spot is invisible. This means that the ambistar is no longer observed as a QSO.

Hence a *typical QSO will almost never show a blueshift*. Certainly there must necessarily be blueshifted *ambistars*, but they should look like ordinary stars – if they are observable at all (their luminosity will be several orders of magnitude lower than a typical QSO).

2.12. Conclusions

A comparison with observations (for example as summarized in *Physica Scripta*, 1978) seems to indicate that our model is reconcilable with quite a few of the most prominent observed properties of QSOs.

The usual view that QSOs are at 'cosmological' distances has not been supported by recent observations. In particular, the different redshifts of objects which are apparently close together in space seem to call for a non-cosmological interpretation. The mechanism suggested in this paper may provide a reasonable explanation.

Of course, our results are model dependent and many serious problems remain to be solved before we can obtain an acceptable theory of the QSOs. However, our study indicates that the assumption of annihilation as a possible energy source deserves to be taken seriously.

3. QSO Scenario

Assuming annihilation to be the energy source of QSOs and adopting the Ambistar Model II we arrive at the following scenario for these objects.

1. *The origin of a QSO* is a collision between a koinostar and an antistar. The place of birth is likely to be in the dense core of a galaxy because stellar collisions are most frequent there.

2. The *collision* is not very different from the collision between two stars of the same kind of matter. Unfortunately this process is not very well understood, but existing models seem to indicate that if the collisional velocity is not excessive, a composite star will be formed after a very violent period of minutes or hours. Its mass is probably not less than 90% of the sum of the masses. As the kinetic energy of the impact is added to the sum of the internal energies of the colliding stars, the composite star will initially be very hot and in a state of violent oscillations. The high temperature will speed up the nuclear reactions in the core, but the nuclear energy release during the short collision period will be small compared to the kinetic energy release and will not affect the collisional process appreciably. After a time of the order of years or more, the composite star will settle down to the properties of a normal star of the same mass.

3. These results may be applicable to the brief collisional period during which an ambistar is formed. Annihilation, which is a phenomenon confined to a very thin boundary layer between the two kinds of matter, is not likely to be large enough to change the collisional process. For reasons given in Section 2, we give a tentative description of an ambistar by two semi-empirical *ambistar models*, the first one

referring to impacting bodies with a very large difference in mass, the second one to bodies with comparable masses. The latter model claims to describe a typical QSO.

4. The rotational axis of the ambistar is determined by the rotation of its parents and especially by the impact parameters. Hence, we expect it to have a *random orientation* in space.

5. The two kinds of matter will be separated by a Leidenfrost layer in which an intense annihilation takes place. The annihilation gives rise to neutrinos which are of no importance, to γ-rays which are largely absorbed inside the ambistar, and to a relativistic e^+e^- gas which will be largely emitted, probably mostly in a direction parallel or antiparallel to the rotational axis. An intense heating will occur, mostly from the absorbed γ-rays, which will make a region around the axis very hot. The hottest region may be a circle around the axis (as in Model I) – perhaps with maximum temperatures at two opposite spots – but it may also be the whole *polar cap* limited by the polar distance α_1. There will be a plasma emission of the solar wind type – most intense above the hottest region which we assume is up to an angle α_1 from the pole. As in the solar wind, the ejection velocity will vary, with the result that density variations build up, eventually resulting in the formation of a number of discrete clouds.

6. The *recoil force* of the emitted e^+e^- gas, light emission and plasma emission will give an efficient *rocket acceleration* of the ambistar. The 'exhaust gases' will be confined to the angle α_1 from the axis.

7. The rocket effect will accelerate the ambistar, possibly up to near the velocity of light. As a galactic core usually has the dimension of 10^{22} cm, the ambistar is likely to remain inside the mother galaxy for at least 10^4 years, which is comparable to its lifetime. An escape is possible if the birthplace is in the outer region and its lifetime is long enough.

8. The observed properties of an ambistar depend on the location of the observer in relation to the axis.

There are three different regions (see Figure 4):

Within the angle $\alpha < \alpha_1$ from the axis the observer will *see a QSO* which is very hot (broad emission lines) *through the 'exhaust gases'* of the rocket which consist of a number of discrete clouds. These may cool down rather rapidly after the emission, so the absorption lines may be sharp. At its birth the QSO has the same redshift as its mother galaxy, but due to the rocket effect this will change – usually increase. The redshift of the exhaust clouds will be smaller than that of the QSO. It may be larger or smaller than that of the mother galaxy.

9. If $\alpha > \alpha_1$ no absorption from the exhaust clouds will be observed. However, during its path through the galaxy the QSO may pass behind normal interstellar clouds, which will cause an absorption. The redshift of these should be the same as that of the galaxy. (This will happen also for $\alpha < \alpha_1$.) For large values of α, the redshift seen from the galaxy coordinate system will be smaller. At the same time the luminosity will decrease because an observer will see the hot region under a less

favourable angle. When we reach $\alpha_1 + 90°$, the hot region will be invisible and the luminosity will fall by several orders of magnitude.

10. When a certain angle α_2 is reached we pass from redshift to blueshift, seen from the coordinate system of the galaxy. The value of α_2 is always $> 90°$ and it approaches 180° if $v \to c$. As the galaxy is generally redshifted we have to go up to a still larger angle α_3 in order to change from redshift to blueshift *in our coordinate system*. When we have reached α_3 we are likely to see nothing or very little of the hot polar region.

11. Hence, *there should exist blueshifted ambistars*, but they will not look any different from ordinary stars. Owing to the annihilation heating, their luminosity may be, perhaps, 10 or 100 times larger than that of an ordinary star but *they will not be identified with QSOs* which normally are $> 10^5$ times more luminous.

Hence, the *absence of observed blueshifts is not an argument against our local acceleration model.*

12. The energy release of an observed QSO has so far always been calculated under the assumption of an isotropic emission of radiation. According to our model the emission is highly anisotropic and the usual values should be reduced by a factor probably not exceeding 10. Further, because QSOs may be located at distances much smaller than the 'cosmological' distances, the energy release figures may be revised downwards by one or perhaps several orders of magnitude.

13. A QSO will become an ordinary star when the mass of the smaller component is completely annihilated. The lifetime of a QSO could not exceed $T = 2\, M_s c^2/P$, where M_s is the mass of the small star. With $M = 10^{33}$ g and $P = 10^{42}$ erg s^{-1} we find $T = 2 \times 10^{12}$ s $\approx 10^5$ yr. As the total number of known QSOs is of the order 10^3, there must be more than 10^{-2} stellar collisions per year leading to the formation of observable QSOs.

14. *A Seyfert galaxy* may represent the childhood of a QSO, when it does not yet have a large velocity in relation to its mother galaxy. It is also possible that these objects are produced by a collision between objects of very different masses, so that they should be described by Model I.

Acknowledgments

This research was funded by the following grant: NSF-AST76-15521 of the Galactic and Extragalactic Astronomy Program of the National Science Foundation.

The present paper is a development of ideas worked out at the Plasma Physics Institute, The Royal Institute of Technology, Stockholm, and presented in TRITA EPP 78-11. I wish to thank Drs P. Carlqvist and B. Bonnevier of this Institute, and Dr B. Laurent of the Physics Institute, Stockholm University, for many discussions and kind help. Further work was done at the Applied Physics and Information Science Department of the University of California at San Diego, La Jolla, California, where I have profited from discussions with Drs W. B. Thompson, M. Burbidge and A. Mendis. I have also received kind help and advice from Messrs J. Vincent and D. Brin and Drs A. Marscher and H. Smith. I wish to thank Mrs Lola Lindsay who has helped me with the editing.

References

Alfvén, H.: 1965, *Rev. Mod. Phys.* **37** (4), 652.

Alfvén, H.: 1971, *Physics Today* **24** (2), 28.

Alfvén, H.: 1977a, *Rev. Geophys. Space Phys.* **15**, No. 3, 271.

Alfvén, H.: 1977b, in G. Ekspong and S. Nilsson (eds), *Antinucleon–Nucleon Interactions* (Wenner-Gren, Vol. 29), Pergamon Press, Oxford and New York, p. 261.

Alfvén, H.: 1978, TRITA-EPP-78-11, Royal Institute of Technology, Stockholm, Sweden.

Burbidge, G. R., Jones, T. W. and O'Dell, S. L.: 1974, *Astrophys. J.* **193**, 43.

Burbidge, E. M. and Burbidge, G. R.: 1978, *Physica Scripta*, **17** (3).

Carlqvist, P. and Laurent, B.: 1976a, *Nature* **260**, 225.

Carlqvist, P. and Laurent, B.: 1976b, Reply to G. Steigman 'The Cosmic X-Ray Background', *Nature* **262**, 821.

Colgate, S. A.: 1967, *Ap. J.* **150**, 163.

Dohnani, J. S.: 1976, in H. Elsasser and H. Fechtig (eds), *Interplanetary Dust and Zodiacal Light*, Springer-Verlag, p. 185.

Elvius, A.: 1970, *IAU Symp.* **44**, 306.

Fälthammar, C.-G., Akasofu, S.-I. and Alfvén, H.: 1978, *Nature* **275**, No. 5677, 185.

Lehnert, B.: 1977, *Astrophys. Space Sci.* **46**, 61.

Lehnert, B.: 1978, *Astrophys. Space Sci.* **53**, 459.

Omnès, R.: 1971, *Astron. Astrophys.* **10**, 228.

Sanders, R. M.: 1970, *Ap. J.* **162**, 793.

Seidle, F. and Cameron, A. G. W.: 1972, *Astrophys. Space Sci.* **15**, 44.

Spitzer, L. and Saslow, W. C.: 1966, *Ap. J.* **143**, 400.

Sofia, S., van Horn, H. M.: 1974, *Astrophys. J.* **194**. 593.

Steigman, G.: 1976a, *Ann. Rev. Astron. Astrophys.* **14**, 339.

Steigman, G.: 1976b, *Nature* **262**, 821.

Thompson, W.: 1978, Private communication.

Thompson, W. B. and Rogers, S.: 1979, *Nature*.

Vincent, J.: 1976, TRITA-EPP-76-12, Royal Institute of Technology, Stockholm, Sweden.

White, R. S., Rayan, J. M., Wilson, R. B. and Zych, A. D.: 1978, *Nature* **271**, 635.

Note added in proof: Dr Per Carlqvist has drawn my attention to the fact that, at relativistic velocities, the backside of an object is visible also at large α-values. This means that our simple QSO model has to be developed by taking account of limb darkening and other effects which produce a non-isotropic emission.