APPEARANCE OF RELATIVISTICALLY EXPANDING RADIO SOURCES

By M. J. REES
Department of Applied Mathematics and Theoretical Physics, University of Cambridge

In this article it is suggested that the central parts of some radio sources may expand with relativistic velocities. Relativistic effects could then have a decisive influence on the observable properties of these sources. In particular, the flux from a radio source expanding with relativistic velocity can change sufficiently rapidly to account for the variations observed in some sources, even if they are at cosmological distances. A related relativistic effect would imply that the ages of some types of radio sources may be significantly less than the usual estimates.

Variable Radio Sources

Intensity variations[1-3] have been observed in several radio sources associated with quasi-stellar objects, the red-shifts of which indicate that they are probably at cosmological distances. Well-known arguments concerning self-absorption[4,5] enable us to place a lower limit on the dimensions of a source which is at a known distance (if the radio flux is synchrotron radiation), and it has proved difficult to understand how a source at a cosmological distance can vary with the observed rapidity unless its size is less than this limit. This problem arises if the assumption is made that the 'time-scale' of the variations cannot be much less than the time light would take to cross the emitting region. If[6,7] (*a*) the variations are periodic, or (*b*) they result from changes in the brightness of a region of fixed size, this assumption is certainly necessary, but I shall describe a type of model where special relativistic effects arise which permit it to be relaxed.

In the model proposed, the source is assumed to be spherical and the radio variations are principally due to changes in its apparent diameter rather than in its surface brightness (in contrast to (*b*)). We shall show that, if the boundary of the source expands with velocity $\sim c$, the apparent rate of increase in its angular size and luminosity can be extremely high. Before discussing the physics of the model, and arguing the reasonableness of relativistic velocities, we shall illustrate its essential geometrical properties.

Consider a sphere, centre S, the surface of which expands with radial velocity v from zero initial radius. An observer O at a large distance R from S (and at rest relative to S) will observe an increase in the apparent size of the sphere. If $v \ll c$ the observed angular diameter will be $2\frac{v}{R}t$, where t is the time measured from the moment when the expansion is seen to begin. However if $v \sim c$ this result needs modification. The locus of points from which radiation reaches the observer at time t is not a sphere, but a spheroid with S as focus, axis along SO, eccentricity v/c and semi-latus rectum vt, as shown in Fig. 1. Owing to aberration, the parts with velocity perpendicular to the observer are invisible if the sphere is opaque, and the apparent limb, in fact, has a velocity making an angle $\cos^{-1} v/c$ ($\sin^{-1} = 1/\gamma$, where $\gamma = (1-v^2/c^2)^{-\frac{1}{2}}$) with SO. Furthermore the apparent component of velocity of the limb at right angles to the line of sight is γv (which can be $\gg c$ if γ is large) and the observed angular diameter of the sphere at time t is $2\gamma vt/R$. If, for example, $\gamma = 5$, the apparent diameter of the source will increase by almost 10 light years each year. Because the observed intensity of a source, for a given surface brightness, is proportional to the apparent size, it is already clear that an expanding source could exhibit a rate of increase of flux density high enough to explain the observations.

This geometrical fact is obviously relevant to a variety of physical models, of which only one will be described here. Suppose that the source consists of a massive object (probably identifiable with a quasi-stellar object) which accelerates particles to relativistic energies. Suppose also that the surrounding magnetic field is weak, in the sense that $H^2/8\pi$ is small compared with the kinetic energy density of the particles. A burst of relativistic particles ejected from the massive object will not be confined by the field, but will expand outwards, 'dragging' the field with it (that is, there will not be an electric field in a reference frame sharing the mean outward motion of the particles, though there will generally be in other frames). This explosion will have a relativistic velocity provided that the thermal gas density is small. If we assume for simplicity that the outward radial velocity is constant, we have an expanding shell resembling the sphere already described.

The electron density and the field strength will decrease as the shell expands, and the spectrum of the synchrotron radiation will alter. The total observed flux at time t is obtained by integrating the contributions from all parts of the shell, but this calculation is complicated by the fact that the emission from different parts was emitted at different stages in the expansion. Also the Doppler blue-shift varies from γ on the limb to $\gamma(1+v/c)$ at the

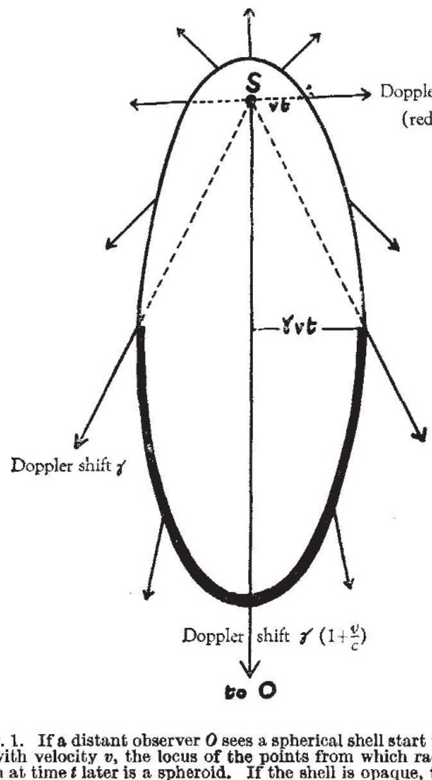

Fig. 1. If a distant observer O sees a spherical shell start to expand from S with velocity v, the locus of the points from which radiation reaches him at time t later is a spheroid. If the shell is opaque, the only visible parts are those the velocity of which makes an angle $< \cos^{-1} v/c$ with SO. These parts all have a Doppler blue-shift $> \gamma$, and the limb has an apparent transverse velocity γv

centre. The total flux from the shell obviously cannot be determined exactly without specifying the detailed behaviour of the model during the expansion. However, the problem is simpler if we restrict attention to low frequencies, for the following reason. The spectral index of the radiation from each part of the source will be 2·5 at frequencies at which synchrotron self-absorption occurs ($< \nu_c$, say). The shape of the spectrum at higher frequencies depends on the energy spectrum of the electrons. ν_c will decrease as the expansion proceeds, but at sufficiently low frequencies of observation (or for small t) all the contributions to the flux will have a spectrum of slope 2·5, and the spectrum of the whole shell will have this slope. The observed flux density will then exceed that from a static source with the same apparent size and magnetic field $\bar{H}$ (where $\bar{H}$ is a mean value of the field strength in the shell when the radiation is emitted) by a factor $\sim\gamma^{\frac{1}{2}}$.

Such a model might apply to 3C 273, the variability of which is well established at several frequencies. The hardest observations to explain[2] (which consequently constitute the most crucial test of any model) are the increase of ~ 6 flux units (F.U.) over a 3-year period, in the flux density at 1,400 Mc/s (the lowest frequency at which variations have been detected). Maltby and Moffet[2] have shown that this can be understood on the basis of a non-exploding model only if H has the improbably small value of $< 10^{-4}$ gauss. If, however, a source at the distance of 3C 273 were to start to explode with a velocity corresponding to $\gamma = 5$, and if H (measured in a frame sharing the mean particle motion) $\sim 10^{-2}$ gauss, the flux density would have risen to ~ 15 F.U. in 3 years, which is greater than is required to explain the data. The parts of the shell which would contribute most of this flux have a Doppler blue-shift > 5, and therefore the radiation received at 1,400 Mc/s would all have been emitted at frequencies below 300 Mc/s. Furthermore, after 3 years, these parts would be ~ 100 light years from S, so we would require ν_c (a decreasing function of distance from S) to be $\gtrsim 300$ Mc/s out to this distance, which is not an unreasonable requirement. The non-variable flux from 3C 273 at frequencies below 1,000 Mc/s must originate in a larger region surrounding the variable component, and its spectrum would mask the steep slope of the low-frequency spectrum of the exploding source. The spectrum of the shell at higher frequencies (or at later stages in its expansion when ν_c has decreased) is more difficult to calculate, because some of the radiation would come from transparent regions. We would expect the highly blue-shifted part of the source with velocity almost towards the observer to be the first to become transparent at a given frequency (though this cannot be definitely stated without detailed calculation of a precise model). It is this part which contributes most of the flux in the early stages of the expansion, so we might expect to observe a decrease in the flux density when it becomes transparent. This decrease could be almost as rapid as the original increase.

It should be emphasized that no attempt has been made to incorporate the optical frequency radiation in the foregoing model for a quasi-stellar radio source. The thermal gas which radiates the lines in the visible spectrum from which the Hubble red-shift is determined presumably has a velocity $\ll c$ relative to the massive object, in contrast to the fast-moving clouds of relativistic electrons in the model. We have, incidentally, neglected a correction factor involving the cosmological red-shift in this model.

The foregoing has demonstrated that the radio variations of quasi-stellar sources do not provide strong evidence for the so-called 'local' theory[6,8] (according to which quasi-stellar radio sources are debris from an explosion in our own or a nearby galaxy, and their red-shifts are a Doppler effect due to high peculiar velocities), since we can account for the available observations on the assumption that the sources are at cosmological distances. Nor is it necessary to invoke 'coherent' radiation mechanisms, which might permit a higher surface brightness temperature to be reached before the onset of self-absorption. If future observations should prove to be inconsistent with this model, a wider range of behaviour could be accommodated by abandoning our assumption of spherical symmetry (for which there is no physical reason, and which was adopted here merely for simplicity), and considering asymmetrical exploding sources with particular orientations.

Other Implications of Relativistic Bulk Motions

The most important feature of the model described in the previous section has been the simple fact that an object moving relativistically in suitable directions may appear to a distant observer to have a transverse velocity much greater than c. The remainder of this article is concerned with other possible implications of this fact for theories of radio sources.

Most strong extragalactic radio sources consist of two or more components separated by distances of up to 10^6 light years[9]. We may assume that their existence is due to some disturbance (of unknown nature) in the associated visible object. If the radiating regions had themselves moved bodily to their observed positions from the parent galaxy, their speed must be relativistic unless their age is $\gg 10^6$ years. Alternative theories[10,11] postulate shock waves or streams of relativistic particles ejected from the galaxy, radio sources being formed as a result of their interaction with intergalactic material or an intergalactic magnetic field. Present observations cannot prove or refute any of these hypotheses, but if more sensitive future observations fail to confirm the presence of a significant amount of intergalactic material (the existence of which is still an open question), theories of the latter type will become less plausible than those according to which both particles and magnetic fields are ejected from galaxies. These 'plasmoids' may well have velocities $\sim c$. No process capable of accelerating them is yet known, but clouds of relativistic particles could certainly be accelerated to relativistic velocities more easily than super-massive stars, as is postulated in the 'local' theory of quasi-stellar radio sources.

If these relativistic velocities exist, the possibility of apparent transverse velocities $\gg c$ implies that the minimum observed lifetime of a source can be less than its observed distance from the associated visible object divided by c. (This conclusion also holds if the radio source does not itself move, but is 'triggered' by some influence which propagates out from the visible object with relativistic velocity.) The total energy contained in radio galaxies is, however, generally sufficient to maintain their observed rate of energy output for a time $\gg 10^6$ years, so that there is no reason to suspect that their lifetimes are in fact much shorter. Quasi-stellar sources, on the other hand, radiate enormous energy at optical and infra-red as well as radio frequencies, and the problem of understanding this great power output from a small region is aggravated if their lifetime is long. Furthermore, they are more likely than other astronomical objects to be the sites of explosions violent enough to accelerate clouds of relativistic particles to high velocities. The conjectures which we shall put forward will therefore be particularly relevant to 'double' quasi-stellar radio sources such as 3C 273 and 3C 47 (refs. 12 and 13).

If a 'plasmoid' consisting of relativistic electrons and magnetic fields is ejected with a velocity $v(\sim c)$ its apparent transverse velocity relative to the quasi-stellar radio source can be as great as $\sim\gamma v$ (that is, $\gg c$) if its velocity makes an angle $\sim \cos^{-1} v/c$ with the line of sight. During t years the 'plasmoid' would appear to have moved a transverse distance $\sim\gamma\, vt$ light years, and its actual distance from its point of origin would be $\sim\gamma^2\, vt$ light years. A proper time $\sim\gamma t$ would have elapsed in the 'plasmoid' since the explosion. (If $\gamma \gg 1$ this is approximately equal to the time it would take to reach its observed position if it had moved with a velocity $\sim c$ perpendicular to the line of sight.) Of course it is very unlikely that an object ejected at random would have its velocity oriented at $\cos^{-1} v/c$ to the direction of the observer, especially if $\gamma \gg 1$. But the associated quasi-stellar radio sources may well have ejected a large number of such clouds, which would be too faint to be detected unless they were moving almost towards us. If $\sim 2\gamma^2$ clouds were thrown out with the same velocity, for example, we would expect only $\sim\gamma$ of them to be blue-shifted, and only ~ 1 to have a Doppler blue-shift $>\gamma$; but it is the cloud which does have a large blue-shift, and is therefore bright enough to be detected, which is likely to have the greatest apparent velocity ($\gg c$) perpendicular to the line of sight. The radiation from each cloud would be emitted predominantly in a narrow beam of angle $\cos^{-1} v/c$ pointing in its direction of motion, and we would receive more radiation from the one cloud with large Doppler blue-shift than from all the others combined. These others would appear closer to the quasi-stellar radio source, though we would expect them to be too faint to be detectable individually. The energy in all the clouds (including their kinetic energy) would be no greater than the energy required by other models.

The most attractive feature of the possibility suggested here is that it enables us to adopt a lower estimate for the duration of the superluminous phase of quasi-stellar radio source. Unfortunately the model would not be tenable if the intergalactic density were as high as $\sim 10^{-5}$ atoms/c.c., since the clouds would then be braked too rapidly by the ambient gas.

The foregoing discussion has shown that bulk velocities $\sim c$ may occur in radio sources, and that relativistic effects may drastically alter estimates of the size of a source from its rate of variation, or conversely of its age from its apparent size. In this way we can resolve some of the difficulties which have been encountered in attempts to understand variable radio sources if they are at cosmological distances. It is also possible that the lifetimes of some radio sources and quasi-stellar objects may be substantially shorter than is generally believed.

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LUMINESCENCE CAUSED BY PROTON IMPACT WITH SPECIAL REFERENCE TO THE LUNAR SURFACE

By J. SCHUTTEN and TH. VAN DIJK
F.O.M. Institute for Atomic and Molecular Physics*, Amsterdam, The Netherlands

RECENTLY, Derham and Geake reported[1,2] some results of laboratory experiments on the luminescence of meteorites by proton impact in the keV-region. The figures supplied by them, however, are mainly relative. Because we are able to perform absolute measurements on excitation by proton and electron beams, we decided to carry out a similar investigation. The apparatus was calibrated by means of a standard tungsten ribbon lamp (a description of the apparatus and the calibration procedure has been given elsewhere[3,4]). Some of our results are given in Fig. 1. The graphs show the luminescence of the meteorites Holbrook, Arispe and Odessa, the lava Fuertaventura and molecular hydrogen, under proton bombardment with an energy of 30 keV. The choice of this energy results from a suggestion made by Kopal[5], who supposed that a correlation exists between solar flares and lunar luminescence. The observed time lag was between 8 and 48 h, whereas an energy of 30 keV corresponds to a time lag of about 26 h.

For the reason that our measurements gave very low excitation values, we also measured the luminescence of willemite. The results are plotted as curves 1 and 3 in Fig. 2.

The maximum number of photons obtained in this way was about 10^7 per μamp and per unit of wave-length.

If it is assumed that the normal flux of protons in the solar wind is $1{\cdot}6 \times 10^{-8}$ cm^2 s^{-1}, that the bandwidth in the optical range is 500 Å, and that there is an area on the lunar surface contributing to the luminescence of 100 km^2, a result of 5×10^{16} photons per sec is obtained. An observer on Earth with a 50-in. telescope at a distance of 385,000 km would receive on the average from this flux 1 photon per 1,000 sec.

* Formerly: F.O.M. Laboratory for Mass Separation.

As we used one of the strongest luminescent materials, we believe it very improbable that even during solar flares, when the intensity of the solar wind increases by a factor of 100, the observed excitation can be caused by proton impact in the keV-region. Even the fact that the lunar night-time is 10^4 times fainter than the normal brightness cannot be explained in this way.

For the luminescence of molecular hydrogen we find about the same values in curve 1 (Fig. 1), assuming a pressure of 10^{-2} torr (this corresponds to a density of about 3×10^{14} cm^{-3}). This seems rather high when the lack of atmosphere and the relatively low escape velocity are considered. Because our laboratory values differ considerably from those of Derham and Geake, we tried to find a reason for this discrepancy.

We believe the following two points to be worth mentioning: (1) In most cases the bombarded target consists of insulating material, so during proton bombardment it is charged up to a potential determined by the conductance of the material, the current density and the proton energy. This means that under laboratory conditions a potential drop develops across the bombarded target. Protons hitting the target surface create secondary electrons, and these electrons are accelerated to the most positive part of the target. As the efficiency of electrons in the keV-region is about 10^5 times higher than that of protons, the luminescence caused by these secondary electrons is several decades greater than the luminescence caused by protons.

This effect becomes clear from a consideration of Fig. 2, where curve 5 corresponds to the light-output by electron-bombardment, and curve 4 by proton-bombardment with an insulating target—which means that a great number of high-energy secondary electrons is formed—whereas