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CONVERSION OF GRAVITATIONAL ENERGY IN QUASARS AND RADIO GALAXIES

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SUMMARY

The enormous radio output of quasars and radio galaxies, following explosions in these objects, is commonly attributed to the conversion of gravitational energy into high-energy particles. In this essay a mechanism is suggested by which this energy-conversion might take place.

If intergalactic space contains a primeval magnetic field, a mass of gas condensing under gravity will convert gravitational energy into magnetic energy. The resulting magnetic field configuration will have singular surfaces known as "sheet pinches". A certain instability at this surface provides a mechanism for converting magnetic energy into high-energy plasma which later forms twin radio clouds.

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It has been known for many years that radio galaxies emit electromagnetic energy at a remarkable rate[1]. For Cygnus A, the radio output L_R (5×10^{44} erg sec^{-1}) is several times the optical output[2]. Since the radiation typically comes from two clouds separated from the galaxy (figure 1), one can deduce from the separation D a lower limit W_R

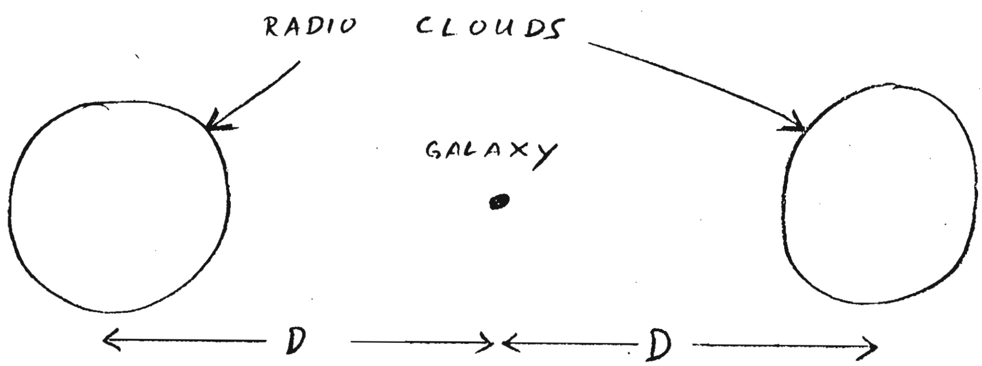

Fig. 1. Typical configuration of radio cloud and galaxy.

to the energy emitted:

$$W_R = \frac{D}{c} L_R . \qquad (1)$$

For Cygnus A, D = 100,000 light years = 10^{23} cm so $W_R = 2\ 10^{57}$ erg. The widely held view that radiation is produced by the synchrotron mechanism leads to bigger estimates W_C of the energy content of the radio clouds. For Cygnus A, $W_C = 3\ 10^{60}$ ergs or $10^6 M_\odot c^2$, where $M_\odot$ is the mass of the sun[3]. The radio-cloud structure implies that this enormous amount of energy was liberated during an explosion of the galaxy.

Quasars[4] experience similar explosions releasing energy of comparable magnitude. In addition, quasars have a high continuum luminosity, marked by outbursts, tentatively ascribed to synchrotron radiation.

Many suggestions have been made for each type of explosion mechanism. Their similarity strongly suggests that the mechanism is the same in both cases. Of the various energy sources suggested for the two phenomena, gravity is common to both and offers a big enough supply of energy.

It now seems possible to duplicate on earth the mechanism by which stars release nuclear energy. Whether or not it will be possible to reproduce the mechanism by which galaxies release gravitational energy is a challenging question which one cannot begin to discuss until the details of the mechanism are established. This essay offers the beginning of such an enquiry.

An explosion is the manifestation of an instability which converts energy stored in one form into some other form or forms. We know that this instability leads to the acceleration of electrons to high energies, which implies that the instability must develop strong electric fields. Instabilities with this property are plasma instabilities.

Although the ultimate source of energy released by the instability is presumed to be gravity, it does not follow that the stored energy is gravitational. Indeed, this seems unlikely. High gravitational energy density resides in, and is therefore imparted to, a high-density gas. But to accelerate particles to high energy, it is necessary to transfer high energy density to a low plasma density. It is possible that the gravitational energy is released in some intermediate form, which is then converted efficiently into high-energy particles, but neither radio galaxies nor quasars offer any evidence for such an intermediate form.

This impasse may be avoided by supposing that the stored energy is not gravitational. The form most appropriate for our purposes is magnetic energy, since this can be released by a plasma instability in a region of low-density plasma where it will produce high-energy particles. We know, moreover, that each radio emitter (if it operates by the synchrotron mechanism) must have a magnetic field. The question which now faces us is the origin and nature of this field. The generation of galactic magnetic fields by dynamo action has not been proved impossible, but it has not been shown to be possible, either. It is therefore preferable to assume that the field is primeval.

Let us now consider what would happen if an object of large mass M were to condense out of a region of intergalactic space of radius R_0 containing a plasma of low density ρ_0 and a weak magnetic field of strength B_0. Then

$$M = \frac{4\pi}{3} R_0^3 \rho_0 \qquad (2)$$

and the magnetic flux Φ (which also is conserved) satisfies

$$\Phi = \pi R_0^2 B_0 . \qquad (3)$$

The formation of such an object is possible only if the gravitational attractive force outweighs the net repulsive magnetic force. The condition for this is

$$M > \frac{1}{\pi} \left(\frac{5}{12G}\right)^{\frac{1}{2}} \Phi \approx 10^3 \Phi. \tag{4}$$

Since $M \propto R_0^3$ and $\Phi \propto R_0^2$, this condition can be satisfied only for values of R_0, M and Φ exceeding critical values:

$$R_{0c} = 10^3 B_0 \rho_0^{-1} \tag{5}$$

$$M_c = 4\ 10^9 B_0^3 \rho_0^{-2} \tag{6}$$

$$\Phi_c = 3\ 10^6 B_0^3 \rho_0^{-2}. \tag{7}$$

We can now understand the fact that galaxies have a typical mass of $10^{11} M_\odot$ by assuming that intergalactic gas of density $\rho_0 \approx 10^{-29}$ gm cm^{-3} is permeated by a magnetic field of strength $B_0 \approx 2\ 10^{-8}$ gauss. The associated value of Φ_c is $2\ 10^{41}$ gauss cm^2 which is indeed the order of magnitude of the magnetic fluxes of radio clouds!

As such an object condenses from magnetized intergalactic plasma, the gravitational energy so released W_{GR} will be transformed largely into magnetic energy W_M. If the final radius and magnetic-field strength are R and B,

$$W_{GR} \approx W_M \tag{8}$$

$$W_{GR} \approx \frac{3}{5} GM^2R^{-1} \approx 4\ 10^{-8} M^2 R^{-1} \tag{9}$$

$$W_M \approx \frac{1}{4} B^2 R^3. \tag{10}$$

The magnetic field has further significance. Since plasma is constrained to flow along field lines, it provides a "funnel" guiding intergalactic gas into the condensing object. Also it can transfer angular momentum from the object to intergalactic space, so permitting the formation of objects as compact as a quasar or galactic nucleus. Indeed, it seems natural to regard a quasar as the beginning of a galaxy: the nucleus of a galaxy before the rest of the galaxy has formed.

If the primeval magnetic field is approximately uniform over the sphere of radius R_0 , the field of the condensed object will be basically dipolar. However, it cannot be a normal dipole field, since it is coupled to intergalactic space. If the surrounding plasma has low but non-zero density, the magnetic field will tend to be force-free. We find that it can be force-free everywhere except on a certain surface across which the field must change direction, as shown in figure 2. At this surface,

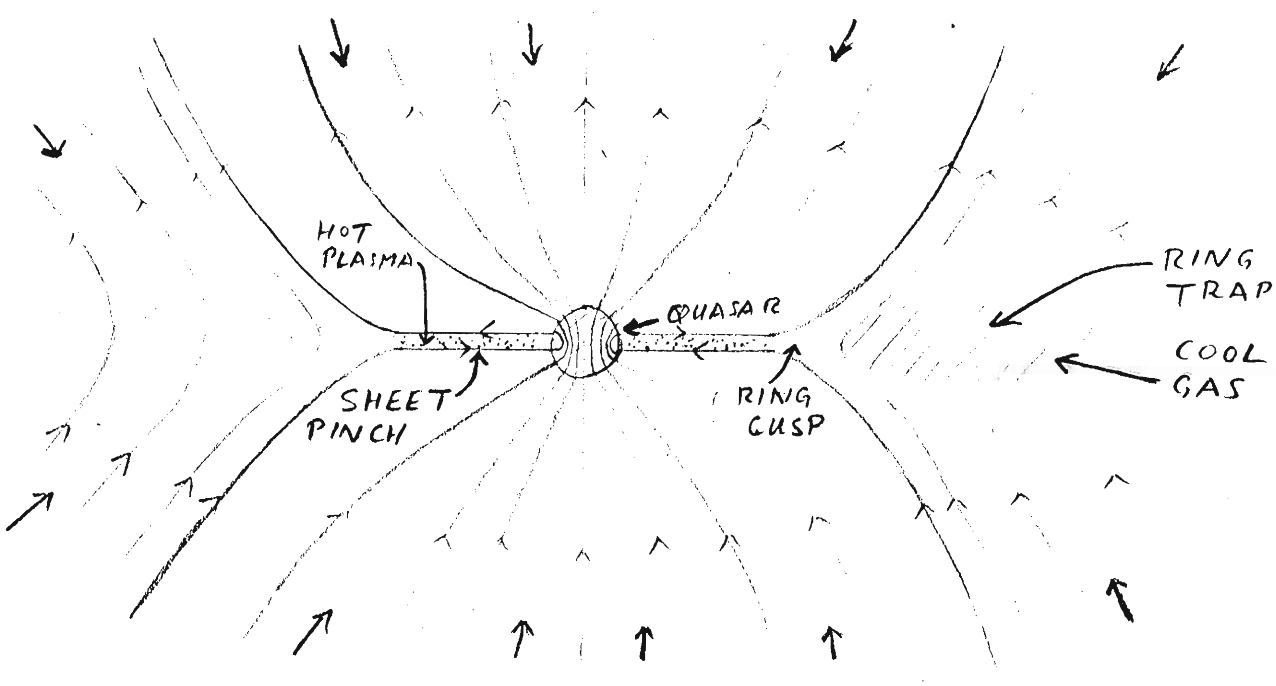

Fig. 2. Schematic model (cylindrically symmetric) of quasar, including sheet pinch and ring trap containing cool gas. Lines indicate magnetic field. Arrows indicate gas flow.

there must be a thin layer of high-pressure plasma to balance the adjacent magnetic pressure. If the plasma density is low, the temperature must be correspondingly high. Such a configuration is known in plasma physics as a "sheet pinch" [5].

Figure 2 now offers a schematic model of a quasar. The emission lines originate at the central object, but the optical and radio continuum may be ascribed to synchrotron radiation from the sheet pinch.

It is significant that the sheet-pinch surrounding a quasar will terminate in ring cusp configuration, outside of which the field-lines form a ring-shape trap for accreting plasma. Plasma collecting here will cool, and it is natural to identify this gas with absorption lines observed in the spectra of some quasars.

The sheet pinch is subject to the tearing-mode resistive instability[6] which is apparently also the energy-release mechanism of solar flares[7]. The "explosion" of a quasar may therefore be identified with a "galactic flare" which is a mechanism for rapid recoupling of magnetic field lines, the released energy going to heat the plasma and accelerate some particles to high energies. It appears that a sheet pinch is a metastable configuration and that the flare mechanism is an explosive instability[8] which can occur on any scale. Small-scale flares provide an explanation of the optical and radio outbursts observed in quasars.

When a large flare occurs, part of the high-energy plasma will be attached to field-lines tied to the quasar, forming a"radiation belt" which would be a source of intense but short-lived radiation. The remainder of the high-energy plasma would be ejected by magnetic catapult action towards the Y-type neutral ring. (Figure 3.) The plasma must here divide into two parts so that, finally, two radio clouds would be produced. (Figure 4.)

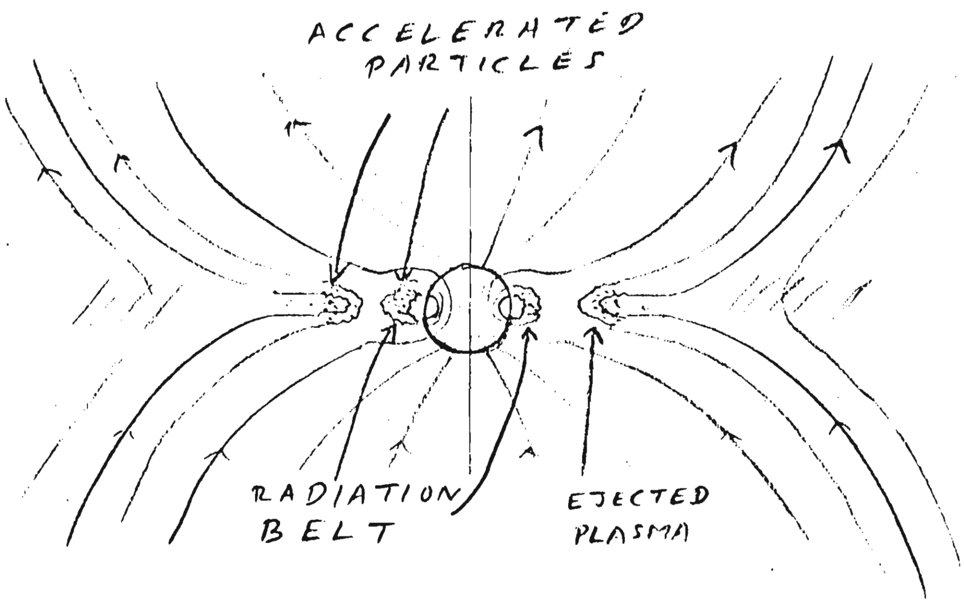

Fig. 3. Result of galactic flare.

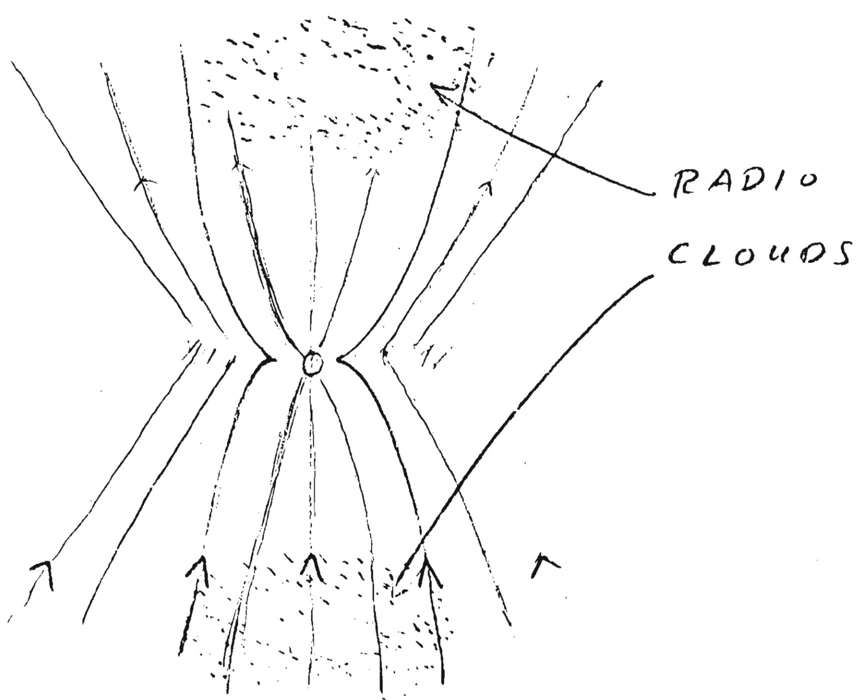

Fig. 4. Simplified representation of formation of twin radio clouds following flare in quasar.

We may now enquire into the magnetic-field pattern to be associated with a radio galaxy. As more mass is accreted, the magnetic field becomes less effective in getting rid of angular momentum and eventually ceases to do so. Further accretion then leads to the formation of a large object, identified with a galaxy, rather than a compact one. Assuming that some flares occurred at the quasar stage, the field pattern will be as shown in figure 5. As more mass collects in the ring trap the disk-shape pinch will collapse into a ring X-type neutral line, as in figure 6. Further

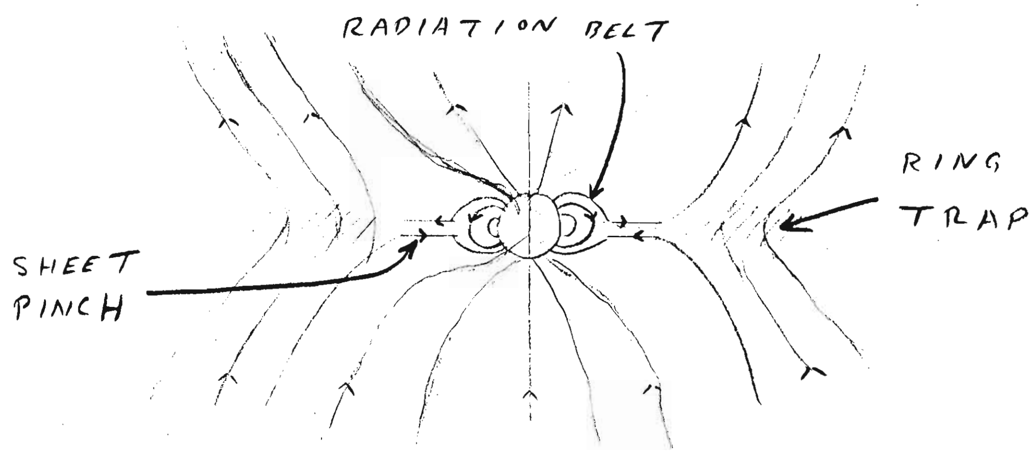

Fig. 5. Field configuration in quasar after major flare.

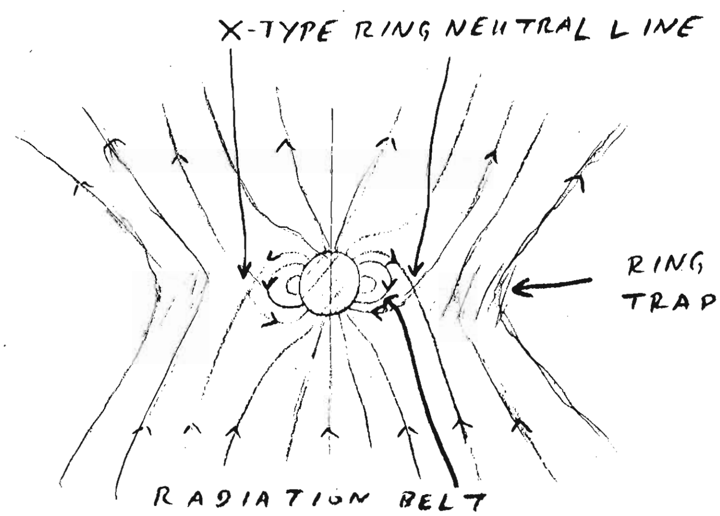

Fig. 6. Change in field configuration caused by increased weight of gas in ring trap.

accretion will convert this into a cylindrical sheet pinch, as in figure 7.

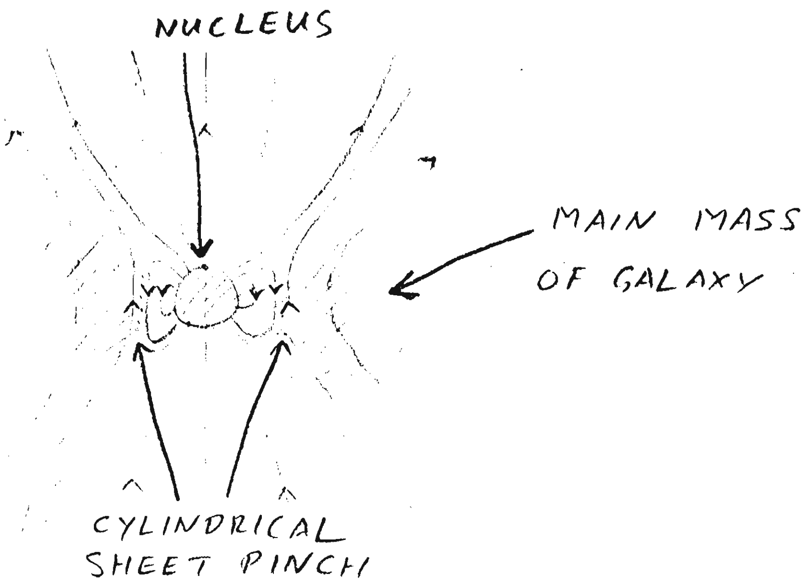

Fig. 7. Further increase in weight of gas in ring trap leads to formation of cylindrical sheet pinch. Proposed typical configuration for radio galaxies.

If a major flare occurs in this configuration, it would give rise to the ejection of two radio clouds in opposite direction, as in figure 8. This implies

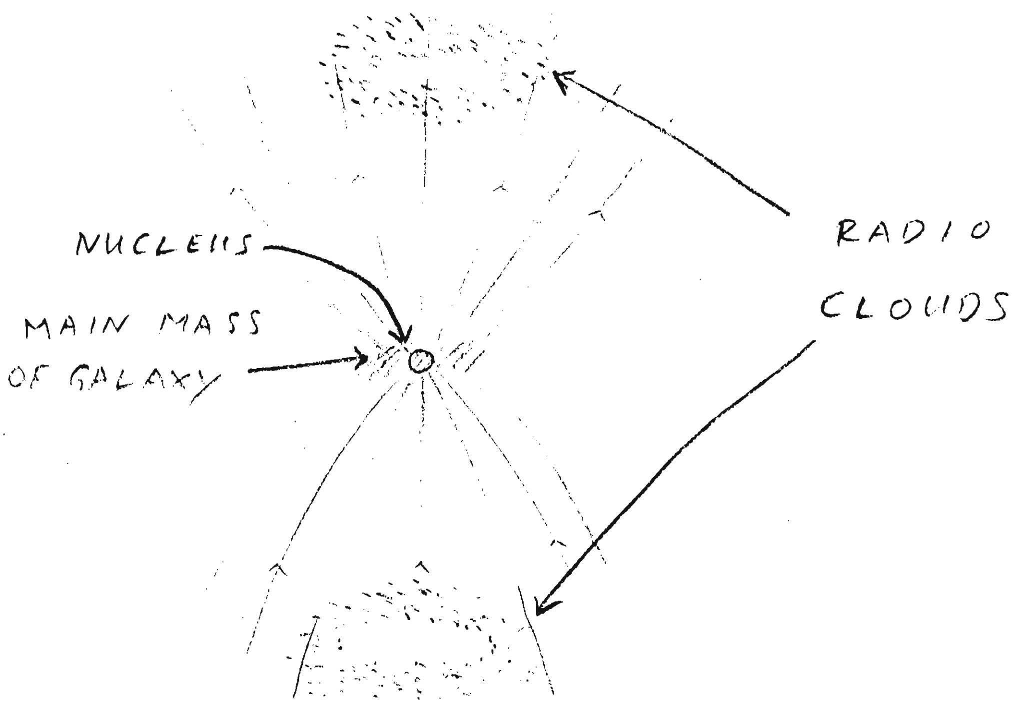

Fig. 8. Simplified representation of formation of twin radio clouds following flare in radio galaxy.

that the topology of a radio cloud is basically that of a "smoke ring", although this shape may become highly distorted and be difficult to recognize as such with present-day radio telescopes.

In conclusion, we may ask whether the mechanism we have proposed could explain the magnitude of the energy released by Cygnus A. The magnetic flux of each radio cloud is estimated to be $2\ 10^{42}$ gauss cm^2, so that the flux through the nucleus must be about the same, implying a mass of $10^{12} M_{\odot}$. The galaxy must be more massive still. The nucleus of the galaxy has the large radius of 2 kpc, so that the magnetic field must be 10^{-2} gauss, and the stored magnetic energy about 10^{61} ergs. Hence the stored energy is indeed of the right order of magnitude to explain the observed radio clouds.

It will not be possible to make similar estimates for quasars until the uncertainties concerning their distances and sizes are resolved. However, if - as is proposed - a quasar is an early stage of a galactic nucleus, it follows that the gravitational and magnetic energy associated with a quasar will be comparable with that associated with a radio galaxy. Furthermore, the high continuous luminosity of quasars may be ascribed to a similar energy conversion process due to sustained accretion. For instance, an object like the nucleus of Cygnus A could emit continuum radiation at 10^{46} erg sec^{-1} (typical of a quasar) if it were accreting mass at a rate of 10^4 $M_{\odot}$ $year^{-1}$, a rate which would double its mass in $2\ 10^8$ years.

If these ideas bear the test of time, we may be able to understand the conversion of gravitational energy into electromagnetic energy in many cosmical phenomena - quasars, radio galaxies, and also cosmic rays.

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Peter A. Sturrock, Professor of Space Science and Astrophysics and Chairman of the Institute for Plasma Research at Stanford University, was born in England in 1924. He studied mathematics at Cambridge University, interrupting his studies to work on radar during the war years, and took his Ph. D. degree in 1951. Since that time he has worked in England, France, Switzerland and the United States on nuclear physics, particle accelerators, microwave tubes, plasma physics and, most recently, space science and astrophysics.

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