THE REVIVED PENROSE PROCESS CAN POWER THE CENTRAL ENGINE IN ACTIVE GALACTIC NUCLEI

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ABSTRACT. Using the fact that the efficiency of the revived (Wagh et al 1985) Penrose process of energy extraction from black holes immersed in electromagnetic fields can be very high (Parthasarathy et al, 1986) we show that this process can comfortably power the 'central engine' in Active Galactic Nuclei. The microphysical Penrose process energized particles will be ultrarelativistic in the asymptotic frame. Hence the kinematical analysis of escaping photons by Piran and Shaham (1977) will be a good approximation to the kinematics of these particles. From this analysis one expects the energized particles to emerge within an angle $\sim 40^o$ above and below the equatorial plane. These energetic particles, which are collimated in the funnel of an accretion disk and further on by the magnetic field, then, form supersonic, relativistic, bilateral jets. The relativistic γ factor for such jets can be expected to be ~ 2 since these ultrarelativistic particles will effectively mimick radiation in 'dragging' the matter already injected inside the funnel. Various implications of high energy extraction efficiency are illustrated.

Recently we have shown that the Penrose process of extracting energy from rotating black holes in electromagnetic fields, i.e., the magnetic Penrose process (MPP) is not only astrophysically potent (Wagh et al, 1985) but a very highly efficient way of doing it also (Parthasarathy et al, 1986). The efficiency per (relativistic or non-relativistic) event of energy extraction is given by

$$\eta \sim e_3\Phi/m_1 \sim (e_3/m_1)M_8B.10^{-8} . \qquad (1)$$

In (1) $\Phi = -\underset{\sim}{A}.\partial/\underset{\sim}{\partial}t$, where $\underset{\sim}{A}$ is the four-potential of the axisymmetric, perturbative, and stationary electromagnetic field, and $\partial/\underset{\sim}{\partial}t$ is the static Killing vector of the Kerr geometry, is the electrostatic

G. Swarup and V. K. Kapahi (eds.), Quasars, 395–398 .

https://doi.org/10.1017/S0074180900153057 Published online by Cambridge University Press

potential as measured by the static observer. Also e_3 is the charge of an escaping particle while m_1 is the mass of an incident particle. The last step of (1) follows from the dipole field approximation. Here M_8 is the black hole mass in units of $10^8\ M_o$ and B is the asymptotic magnetic field in guass. As is evident $\eta \gtrsim 1$ for realistic situations, $B \sim 10^{-6}$ gauss, $e_3/m_1 \sim 10^{17-14}$ esu/g- the specific charge of an electron/proton. This efficiency estimate is valid near the static limit.

The luminosity that can arise due to the MPP is

$$L_{MPP} \sim \beta \langle n \rangle\ B M_8 \dot{M} . 10^{55}\ \text{erg/s} \quad (r \sim 2M) \quad . \tag{2}$$

Here β is the photon production efficiency, $\dot{M}$ -accretion rate in units of M_o per year, and $\langle n \rangle$ denotes 'average MPP events' that generate the luminosity. If the photons are produced by the synchrotron mechanism, then, $\beta \sim 0.1$. By way of comparison, the Blandford-Znajek (1977) luminosity is

$$L_{BZ} \sim 2.8 M_8^2 B^2\ 10^{37} \quad \text{erg/s.}$$

By demanding that $L_{MPP} \sim L_{BZ}$ we obtain

$$\langle n \rangle \sim (M_8 B/\dot{M})\ .\ 10^{-17}$$

implying that even if the MPP is rare it still can power the 'central engine' in active galactic nuclei.

If the 'collisional MPP' (CMPP) of the type envisaged in non-magnetic scenarios by Piran and Shaham (1977) is to be important, then

$$\begin{aligned} \text{mean free path} = \lambda_{CMPP} &\sim 6.64\ (v e^{\nu}/\sigma)\ (M_8^2/\dot{M})\ .\ 10^{-12} \\ &\lesssim \text{proper thickness of target zone} \\ &\quad \text{(around } r \sim 2M) = \varepsilon M \end{aligned} \tag{3}$$

where v (= v/c) is the mean velocity of the accreting particles in the local frame, $\exp(\nu)$ is the metric coefficient of the Kerr space-time ($ds^2 = \exp(2\nu)dt^2 + $ ---), and $\sigma = \sigma_T\ f(\alpha)$ is the cross-section, α being a suitable dimensionless parameter. This places a constraint on the accretion rate as

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$$vM_8 \; e^{\nu}/\varepsilon \; f(\alpha) \leq \dot{M} \quad , \quad \sigma_T = 0.67 \times 10^{-24} \; \mathrm{cm}^2 \qquad (4)$$

Because $v \sim 10^{-2}$ -- 10^{-3} in astrophysical plasmas (and other factors of order unity) it is evident that unduly high accretion rates are not required. The CMPP, thus, can be expected to solve the problem of scarcity of fuel (Frank, 1978) without placing sèvere constraints on the galactic structure and evolution.

Demanding further that

$$t_{CMPP} = \lambda_{CMPP} / c \sim t_{sy} \lesssim t_{in-C} \qquad (5)$$

where t_{sy} is the synchrotron lifetime and t_{in-C} is the inverse - Compton lifetime of electrons, we obtain

$$8\pi U_{ph} / B^2 \lesssim 1 \qquad (6)$$

where U_{ph} is the photon energy density, as a consistency relation.

Thus, the inverse-Compton losses do not render the CMPP ineffective as an acceleration mechanism. That this Hoyle-Burbidge-Sargent (1966) condition is compatible with the requirements of the CMPP is not surprising. In view of (3) it can always be arranged to have a sufficiently small mean free path of collisions for sufficiently small velocity v. With a hindsight we can say that from (6) a very high energy extraction efficiency should have been suspected.

Since the CMPP energized particles will be ultrarelativistic in the asymptotic frame, the kinematical analysis of escaping photons by Piran and Shaham (1977) will be a good approximation to the Kinematics of these particles. From their analysis one expects the energized particles to emerge within an angle ~ 40° above and below the equatorial plane. These energetic particles, which are finely collimated inside the funnel of an accretion disk and further on by the magnetic field, then, form supersonic, relativistic bilateral jets. The relativistic γ factor for such jets can be expected to be ~ 2 since these ultrarelativistic particles will effectively mimick radiation in 'dragging' the matter 'already' injected inside the funnel of an accretion disk. This expectation is not at variance with the value of γ as observed in jets of active galactic nuclei.

In conclusion, we have shown that the CMPP can be expected to solve two of the major problems of modelling active galactic nuclei, namely, the fuel problem and the inverse-Compton-catastrophe problem. Although a detailed model is yet to be worked out, these above indications strongly suggest that the CMPP is indeed 'the candidate' for the 'prime mover' in active galactic nuclei.

ACKNOWLEDGEMENTS

A research grant from the Indian Space Research Organization under its RESPOND program is gratefully acknowledged.

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NOTE

A detailed version is submitted to Nature for publication (Wagh, Dhurandhar, and Dadhich 1986, preprint).

https://doi.org/10.1017/S0074180900153057 Published online by Cambridge University Press