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THE CENTRAL ENGINE OF QUASARS AND AGNs: A RELATIVISTIC PROTON RADIATIVE SHOCK

Demosthenes Kazanas and Donald C. Ellison
LHEA, Code 665, NASA/Goddard Space Flight Center, Greenbelt, MD 20771
and
Astronomy Program, University of Maryland, College Park, MD 20742

1. Introduction. Active galactic nuclei (AGNs) and quasars (QSOs) appear to emit roughly equal energy per decade from radio to γ-ray energies (e.g. Ramaty and Lingenfelter 1982). This argues strongly for a non-thermal radiation mechanism (see Rees 1984). In addition, statistical studies have indicated that the spectra of these objects in the IR-UV and 2-50 keV X-ray band, can be fitted very well with power laws of specific indices. These spectral indices do not seem to depend on the luminosity or morphology of the objects (Rothschild et al. 1983; Malkan 1984), and any theory should account for them in a basic and model independent way.

If shocks accelerate relativistic protons via the first-order Fermi mechanism (e.g. Axford 1981), the radiating electrons can be produced as secondaries throughout the source by proton-proton (p-p) collisions and pion decay, thus eliminating Compton losses (Protheroe and Kazanas 1983). As shown by Kazanas (1984), if relativistic electrons are injected at high energies, e^+-e^- pair production results in a steady state electron distribution that is very similar to that observed in AGNs, independent of the details of injection and the dynamics of the source. The conditions required by this mechanism are met in the shock model of Eichler (1984) and Ellison and Eichler (1984) which allows the self-consistent calculation of the shock acceleration efficiency.

2. Model. We assume that a black hole of mass, $M_9 = M/(10^9\ M_\odot)$, accretes gas of density, n, and temperature, T. If the dissipative time scale of the accreting material, τ_{pp}, is longer than the free fall time, τ_{ff}, a steady state radiative shock will develop at $x = R/R_s$, where $R_s = 2GM/c^2$ is the Schwarzschild radius. Inflowing thermal particles with free fall velocity, u, will be shock accelerated and relativistic protons will be produced. These protons will undergo inelastic nuclear collisions to produce pions, i.e., $p + p \rightarrow p + p + \pi^{\pm} + \pi^0$. The pion decay will produce γ-rays, neutrinos, and relativistic electrons which will subsequently produce the observed radiation by synchrotron and inverse Compton emission. Since ~ 50% of the energy flux that goes into relativistic particles is lost to neutrinos (Eichler 1979) and since the shock must form beyond the Schwarzschild radius, the maximum efficiency for this model is considerably less than 1. The maximum luminosity is determined by the ability of the shock accelerated particles to provide sufficient pressure to support the shock against the accreting material. This is determined by the shock dynamics and occurs at ~10% of the Eddington luminosity.

A fraction, Q, of the energy flux crossing the shock is converted into relativistic particles and eventually into radiation. Therefore,

$$L_{tot} = 4\pi R_1^2 \cdot \frac{1}{2} n_1 m_p u_1^3 \cdot Q, \qquad (1)$$

where L_{tot} is the total radiated energy including neutrino losses and the subscript (1) indicates values at the shock. Due to neutrino losses, the observed luminosity, L, will be $L \sim 0.5\ L_{tot}$. Alternatively, if $\langle E_{rel}\rangle$ is the average energy density in relativistic particles, the total luminosity can be expressed as,

$$L_{tot} \simeq 4\pi R_1^3 \langle E_{rel}\rangle/(3\tau_{pp}), \tag{2}$$

where $\tau_{pp} \simeq 1/(\langle n_1\rangle \sigma c) \simeq 2.2\ 10^5\ x_1^{3/2}\ M_9^2\ \dot{m}^{-1}$ sec is the p-p interaction time, σ is the p-p cross section, x_1 is the shock position in Schwarzschild radii, $\langle n_1\rangle$ is the average density inside the shock, and $\dot{m}$ is the accretion rate in $M_\odot$/yr. Equations (1) and (2) determine the shock position. Assuming mass conservation, i.e., $n \simeq 1.2\ 10^9\ x^{-3/2}\ M_9^2\ \dot{m}/cm^3$, and using $\langle E_{rel}\rangle = 3P_{rel}$, where P_{rel} is the relativistic particle pressure, we have

$$\frac{\dot{m}}{M_9} \simeq 11\ \frac{Q}{\eta}, \tag{3}$$

where $\eta = P_{rel}/(n_1 m_p u_1^2)$. Eq. (3) indicates that $\dot{m}/M_9$ is determined solely by the shock efficiency and cannot have an arbitrary value. The efficiencies Q and η (which to good approximation depend only on the shock Mach number) can be calculated self-consistently using the non-linear, steady state solution of Eichler (1984) and Ellison and Eichler (1984). This assumes that a magnetic field is present for the formation of the collisionless shock and the elastic scattering of the accelerated particles. We assume, however, that the magnetic field is not dynamically important and that the Alfvén (or phase) velocity is small compared to the shock velocity. We also require that the mean free path of the highest energy particles be no smaller than R_s so they avoid being swallowed by the black hole and hence can provide the pressure to support the standing shock.

Since both Q and η approach 1 for high Mach numbers, there is a maximum value above which no steady state shock solutions of the type described here exist. If $\dot{m}/M_9$ is greater than this limit, the p-p collisions behind the shock occur so rapidly that there is not sufficient relativistic particle pressure to support the radiative shock.

Using the above relations, the observed non-thermal luminosity, L, becomes

$$L \simeq 1.5 \times 10^{47}\ Q^2\ M_9/(\eta\ x_1) \quad \text{erg/s}. \tag{4}$$

Defining, $F = L/L_E$, where $L_E = 1.3 \times 10^{47}\ M_9$ erg/s, eq. (4) reads

$$F = L/L_E \simeq 1.2\ Q^2/(\eta\ x_1). \tag{5}$$

This indicates that the sources should emit at a given fraction of the Eddington luminosity (L_E), which depends only on x_1, Q, and η.

The value of x_1 can be expressed in terms of the Mach number, M_1, and the upstream temperature as,

$$M_1^2 = 3m_p u_1^2/[5k(T_e + T_p)] \simeq 6.5 \times 10^4/(x_1 T_8), \tag{6}$$

where T_8 is the upstream temperature in units of 10^8 K and is expected to be determined by the balance between X-ray Compton heating and cooling and has been shown to be essentially constant and $\sim 10^8$ K (e.g., Krolik et al. 1981). Consequently, F, depends on only one parameter, M_1 or x_1.

3. Results and Conclusions. By combining eqs. (5) and (6), we can obtain the Eddington efficiency as a function of the shock size or the accretion rate. These relationships are shown in Figs. 1a, and b. A range of upstream temperatures is shown.

The Eddington efficiency drops precipitously with increasing x_1 due to the fact that Q approaches zero as M_1 drops below ~ 4. One therefore expects that there would be an effective upper limit for x_1 (lower limit for M_1) above which the sources are too weak to be seen. At the other extreme, there is a maximum value for F since x_1 can not be arbitrarily small. We have chosen $x_1 \simeq 5$ as a reasonable minimum value of the shock radius. This corresponds to an efficiency, $F \simeq 0.2$.

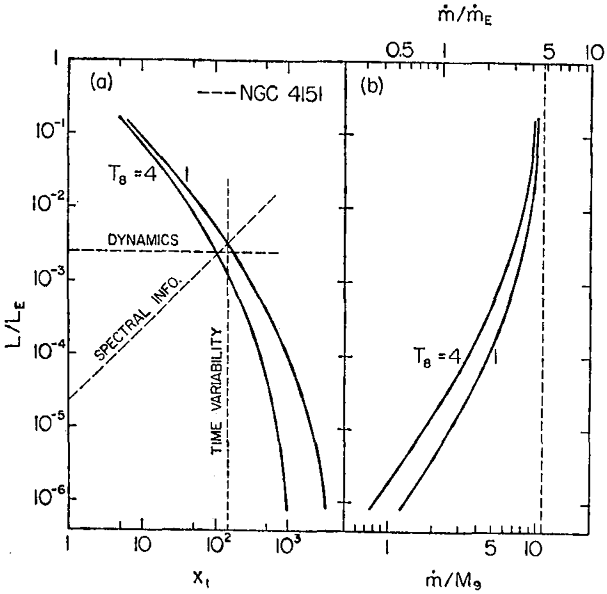

Fig. 1. L/L_E vs. shock position x_1, and accretion rate, $\dot{m}_E = L_E/c^2 = 2.3\ M_9$ solar masses/yr.

We can also express the luminosity as a function of the black hole mass with x_1 as a parameter. Our results can now be directly compared to the correlation between L and M (Fig. 2) found recently by Wandel and Yahil 1985) (W-Y). These authors, by attributing the widths of the H_β line to dynamical motions, and using photoionization arguments to determine the distance of the line emitting clouds, showed that the luminosity of ~ 70 QSOs and Seyfert 1 galaxies is proportional to their mass. In comparing our model, which yields the entire non-thermal luminosity, a bolometric correction raising the points of W-Y by 5-10 should be used. With such a correction, the shock model with $5 \lesssim x_1 \lesssim 150$ reproduces the observations extremely well. The observations indicate that even though the non-thermal radiation from QSOs and AGNs is generally well below the Eddington limit, it is still highly correlated and proportional to the mass. This proportionality is an integral feature of our shock model and results from the fact that $\dot{m} \propto M_9$ (eq. 3). The proportionality constant depends mainly on the p-p strong interaction cross section and results in luminosities well below the Eddington limit in accordance with observations. Also, the fact that no objects in the W-Y compilation are observed to emit much below 0.01 L_E might have an explanation in the sharp decrease in F with $\dot{m}/M_9$ as indicated in Fig. 1b. We consider the straightforward interpretation of this correlation by our model as an indication of the correctness of its basic premises.

The galaxy NGC 4151 affords an additional test of our model. The considerations of W-Y provide an estimate of the mass, $M \simeq 3 \times 10^7\ M_\odot$. This mass along with the observed absolute luminosity, $L \simeq 10^{43}$ erg/s, determine, $F \simeq 2.5 \times 10^{-3}$. This is shown by the horizontal dashed line of Fig. 1a labeled "dynamics". X-ray variability has been established on time scales of $\Delta t \simeq 12$ hours (Mushotzky et al. 1978), indicating a size, $R \simeq c\Delta t \simeq 1.3 \times 10^{15}$ cm. Using the determined mass, this translates into a shock radius, $x_1 \simeq 140$, and is shown in Fig. 1a as "time variability".

Furthermore, measurements of the X-ray spectrum of NGC 4151 (Mushotzky et al. 1978) provide a constraint on the compactness, L/R, within the framework of the non-thermal, e^+-e^- feedback model of AGN spectra (Kazanas and Protheroe 1983; Kazanas 1984); i.e., $L/R \lesssim 10^{28}$ erg/(s-cm). This condition becomes, $F \lesssim 2.3 \times 10^{-5}\ x_1$, and is indicated in Fig. 1a by the line labeled "spectral information". We find the agreement between these independent constraints and our model to be quite remarkable.

In conclusion, we have outlined a model for AGNs and QSOs which is complete in the sense that it simultaneously addresses the source dynamics (i.e. the conversion of accretion energy into radiation) and spectrum (from radio to γ-rays). As shown in Kazanas (1984), the e^+-e^- feedback decouples the spectral signatures from the dynamics, provided that most of the power is injected at energies high enough that the resulting photons are absorbed within the source to produce e^+-e^- pairs. The present model does precisely that, through shock acceleration (Ellison and Eichler 1984). Furthermore, it provides a straightforward physical argument as to why such shocks should occur ($\tau_{pp} > \tau_{ff}$) and also gives estimates of the Eddington efficiencies, F, and sizes, x_1, of these sources. Finally, in its most direct confrontation with observations (Fig. 2), our model provides a natural explanation for the $L \propto M$ correlation. In addition, it also provides the normalization (it is directly related to τ_{pp}) and its value is in remarkable agreement with the data of W-Y.

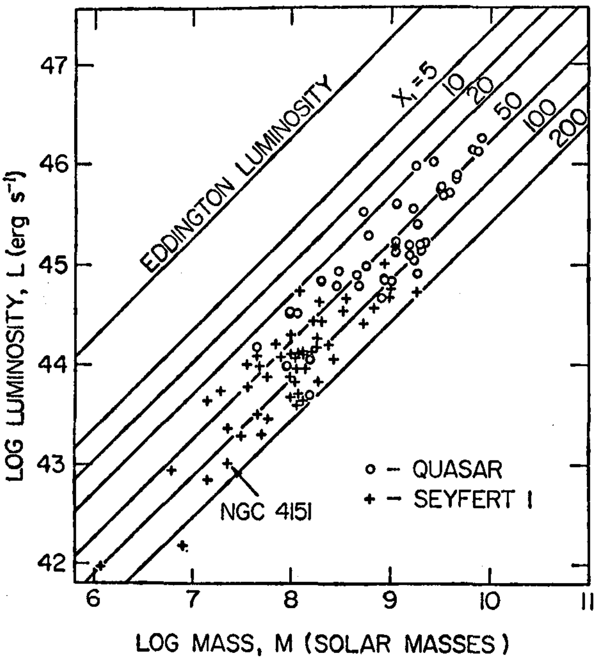

Fig. 2. The lines are from the shock model (using $T_8 = 1$) for shocks which form at various x_1. Points are from Wandel and Yahil.

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