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THERMAL PAIR CLOUD MODELS OF MeV GAMMA RAY EMISSIONS FROM CYGNUS X-1 AND THE GALACTIC CENTER

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Abstract

The HEAO-3 data for the enhanced MeV gamma ray emissions of Cygnus X-1 and the Galactic Center in 1979 can be modeled by thermal emissions from a compact pair-dominated cloud surrounding the black hole. We derive from first principles the structure of such pair clouds and use these results to constrain the mass of the central black hole, the viscosity parameter and other parameters of the innermost accretion flow. We estimate the production and escape of pairs outside the thermal cloud due to collisions of gamma rays with other gamma rays and with x-rays from the disk. The annihilation of such escaped pairs in the cool medium far from the source can lead to detectable narrow 511 keV lines. These results are compared with the variable 511 keV source in the Galactic Center and the upper limits for Cygnus X-1.

Introduction The discovery of a transient gamma ray bump (0.4-few MeV) in the 1979 HEAO-3 spectra of Cygnus X-1 (Ling et al 1987) and the Galactic Center (Riegler et al 1985) provide new insights into the nature of accretion flows near black holes. In a recent paper (Liang and Dermer 1988) the Cygnus X-1 gamma ray bump was interpreted as the Comptonized bremsstrahlung and annihilation emission of a hot (T~400 keV) pair-cloud displacing the innermost x-ray disk. In this paper we report some new results concerning the structure of such a thermal pair cloud based on first priniciples, the application of such a model to both Cygnus X-1 and the Galactic Center to extract useful informations, and the anticipated production of an escaping pair wind from the interaction of the gamma rays with the x-rays of the surrounding disk.

Pair Cloud Structure and the Viscosity Parameter Following the conventional approach to the structure of thin accretion disks (e.g. Shapiro et al 1976), we can derive the spatially averaged density, temperature etc. of the thermal pair cloud in terms of a global viscosity parameter $\tilde{\alpha}$ and cloud radius r via global conservation laws, pair-balance and Coulomb coupling between ions and pairs. Such solutions differ from the thin disk solutions of Kusunose and Takahara (1989) and White and Lightman (1989) in two major respects: a) the thin disk is replaced by a quasi-spherical cloud modeling a thick torus and b) all physical parameters are global spatial averages since we believe "local" quantities are no longer well defined due to long mean-free-paths and the uncertainties of dissipation mechanisms.

There are five structure equations for the five unknowns: luminosity of pair cloud L, proton temperature T_p, lepton temperature T and proton and lepton density $n_{p,e}$. Energy conservation gives:

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$$L(r_*) = L_o\ (1 - 18\ (1{-}b\,(6/r_*)^{1/2}/1.5)\ r_*^{-1}\ (3{-}2b)^{-1}) \quad (1)$$

where $b \leq 1$ is a measure of the "Keplerianess" of the orbital velocity at the innermost stable orbit at $6GM/c^2$. Angular momentum conservation gives:

$$8\pi r^3\ \bar{\alpha}\ p/3 = \dot{M}\,(GMr)^{1/2}\,J\ , \qquad p = n_p(T_p + (1+2z)\,T) + P_{rad},\quad J = (1 - b(6/r_*)^{1/2});\ P_{rad} = \sigma_T\ F(flux)/c \quad (2)$$

which can also be considered as definition of $\bar{\alpha}$. Coulomb coupling gives:

$$f\,r^2 n_p\,\tau_T\,\ell n\Lambda(T_p - T)\,(1 + T_*^{1/2})\ T_*^{-3/2} = 1.2\times10^{-8}\,L\ ;\ \tau_T \equiv n_p\,\sigma_T\,r(1+2z) \quad (3)$$

where $f \leq 1$ is a fudge factor denoting the fraction of heat radiated away to infinity before theplasma spirals into the hole, $T_*=T/mc^2$ and $\ln\Lambda \sim 20$ is the Coulomb log. Pair balance gives (Svensson 1984, Zdziarski 1984) gives L and τ_T in terms of T and proton Thomson depth τ_p:

$$L = 3.7\times10^{28}\ \text{erg/s} \times r \times \ell(T,\tau_p) \quad (4)$$

$$\tau_T = \tau_T(T,\tau_p) \quad (5)$$

where ℓ is the compactness parameter, $z=n_+/n_p$ is pair fraction and $\dot{M}$ is accretion rate ($\sim 10^{-20}L_o$ for 10% energy conversion efficiency). In the limit where $z \gg 1$ and $T_p \gg T$ and assuming b=1, the above equations can be combined to solve for T in terms of $\bar{\alpha}$, since τ_T is now a function of T only:

$$\bar{\alpha} = 70\,f\,\tau_T\,r^{-1/2}\,J(1 + T_*^{1/2})\ T_*^{-3/2}\,(1 - 18\,(1 - \sqrt{6/r_*}/1.5)\ r_*)^{-1} \quad (6)$$

From the HEAO-3 data for Cygnus X-1 we have $T_*=0.8$, $\tau_T=2$, and $r=3\times10^7$ cm ($r_*=20$). We find $\bar{\alpha} \sim 0.1$ for f=1. For the HEAO-3 Galactic Center data preliminary results suggest that the best spectral fit gives $T_*=1.1$, $\tau_T=1.5$ and $r=5\times10^8$ cm (using $\ell \sim 8$ and a source distance of $\sim$ 8.5 kpc). So we find $\bar{\alpha} \sim 0.01$ for f=1 and $M=100\ M_\odot$. We must emphasize that unlike the Cyg X-1 case, the mass and distance for the Galactic Center sources are pure guesses at this point (see, however, discussions in following sections). General solutions of the above structure equations for both the pair-dominated and non-pair-dominated cases will be reported in detail elsewhere (Liang 1990).

<u>Constraints on the Mass and Parameter b</u> From Eq.(1) we see that if we had independent measurements of the gamma luminosity L and the bolometric (x plus gamma) luminosity L_o of a black hole source, since r is determined from spectral fitting and pair balance (cf. last Section), then in principle we can empirical constrain the black hole mass M and the Keplerianess parameter b. For Cyg X-1 these constraints are plotted in Fig. 1 and are consistent with the conventional values. For the Galactic Center we are less certain of L_o because much of the x-ray flux reported in Riegler et al (1985) may be contaminated by background sources (e.g. Cook et al. 1988) due to the large field of view. But we would guess a mass range of hundreds, certainly not millions of solar masses, would be most consistent with the constraints.

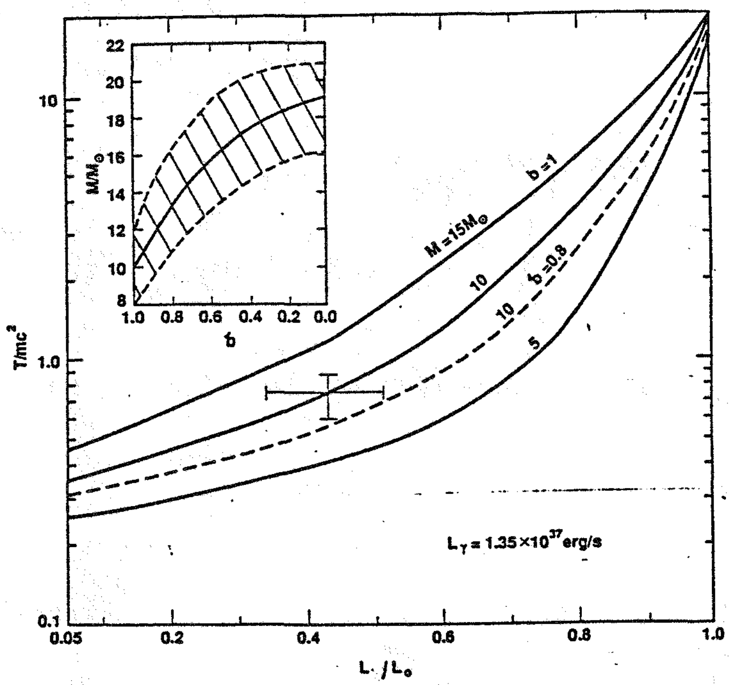

Fig. 1 Comparison of theoretical T-L/L_o relations for sample (M,b) values with the HEAO-3 Cyg X-1 data. b=1 for solid curves and 0.8 for dashed curve. Inset: M values constrained by the HEAO-3 data as function of b.

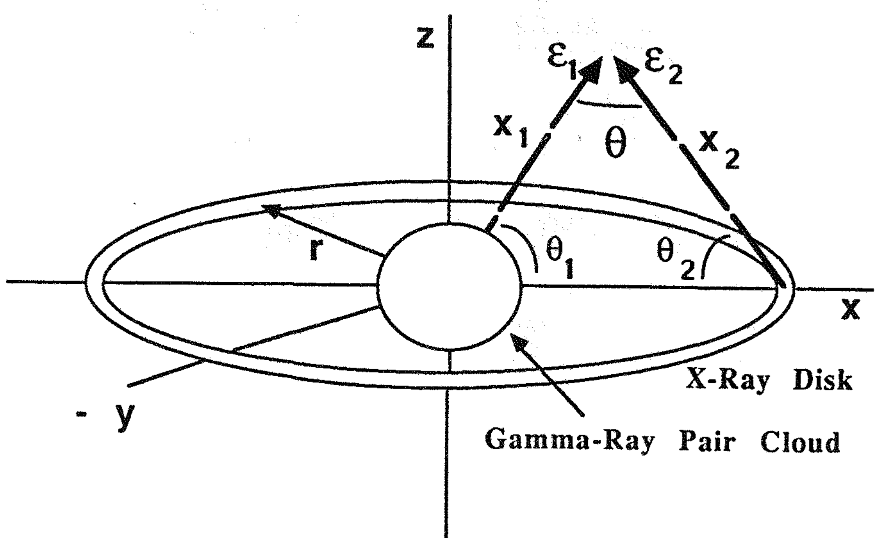

Fig. 2 Geometry of x-ray and gamma ray interactions used in calculating the pair production outside the thermal cloud.

Pair Wind from Gamma-Gamma and Gamma-X Collisions and the 511 keV line Intensity To calculate the pair production from gamma-gamma and gamma-x collisions outside the thermal cloud (i.e. where there are no protons to heat the pairs), we idealize the x-ray disk as a narrow ring (Fig. 2) and use Monte Carlo techniques to evaluate the integrals (Dermer and Liang 1988). We find that for fluxes appropiate to Cyg X-1 the escaping pair luminosity would be ~ 2×10^{41}e+/s. If all of these e+ cool before they annihilate into a 511 keV line of width ~ 1 keV then the expected line intensity would be ~3×10^{-4}ph/s.keV.cm^2, marginally consistent with the upper limit recently reported by Ling et al (1989). Results for the Galactic Center depend on the actual X-ray intensity from the gamma ray point source and must await further analyses of current and future x-ray observations and determination of the true distance to the source.

Conclusions The transient appearance of an ~MeV gamma ray bump in two of the nearest black hole candidates and the correlated appearance of an intense 511 keV line at least for the Galactic Center source strongly suggest that such phenomena are characteristic of black holes. The baseline picture of a thermal pair cloud replacing the innermost region of the accretion flow being responsible for both the continuum and line sources is both aesthetically simple and seems to be consistent with most observational constraints. Future gamma ray observations of these and other black hole candidates (both Galactic and in AGNs) should provide an expanding database to confirm or alter this picture.

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