TITLE **STAR-DISK COLLISIONS IN ACTIVE GALACTIC NUCLEI
AND THE ORIGIN OF THE BROAD LINE REGION**

AUTHOR(S) **W. H. Zurek, T-6
A. Siemiginowska, Center for Astrophysics, Harvard
S. A. Colgate, T-6**

SUBMITTED TO **Proceedings of "Testing the AGN Paradigm"
College Park, Maryland, Oct. 14-16, 1991**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Dec. 5, 1991

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

STAR-DISK COLLISIONS IN ACTIVE GALACTIC NUCLEI AND THE ORIGIN OF THE BROAD LINE REGION

W. H. Zurek, A. Siemiginowska*, and S. A. Colgate
Theoretical Astrophysics, T-6, MS B288
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

Stars of a cluster surrounding the central black hole in an AGN will collide with the accretion disk. For a central black hole of $10^8 M_\odot$ and a cluster with $10^7 - 10^8$ stars within a parsec, one estimates that $\sim 10^4$ such collisions will occur per year. Collisions are hypersonic (Mach number $M \gg 1$). Some of the wake of the star — the disk material shocked by its passage — will follow it out of the disk. Such 'star tails' with the estimated masses $\delta m \sim 10^{25} - 10^{27}$ g subsequently expand, cool and begin to recombine. We propose that — when illuminated by the ionizing flux from the central source — they are likely to be the origin of the observed broad emission lines.

EMITTING CLOUDS IN THE BROAD LINE REGION

Observed properties of the active galactic nuclei span a very broad range of luminosities, spectral characteristics, variability timescales and morphologies (inferred, e.g., from the VLBI data). Such diversity of the observed behavior calls for a comparably broad range of the basic physical parameters of the innermost region, which presumably houses the central 'powerhouse', usually assumed to be a massive ($M \sim 10^8 M_\odot$) black hole surrounded by an accretion disk fed at the rate $\dot{M} \sim 1 M_\odot/\text{year}$ by a surrounding dense ($10^7 - 10^8 M_\odot/\text{pc}^3$) star cluster.¹

In the view of this diversity of the inferred physical conditions in the cores of the AGN's the relative similarity of the observed features of the BLR is quite unexpected. For example the covering fractions are usually within a factor of a few from the typical 10%. Moreover, the physical characteristics of the broad-line emitting regions (densities $\sim 10^9 - 10^{11} \text{ cm}^{-3}$, sizes $\sim 10^{13} \text{ cm}$, etc.) deduced from the observations are also relatively 'AGN-independent'. Thus, the mechanism responsible for the presence of such clouds within the fraction of the central parsec (where BLR is usually placed) appears to be remarkably insensitive to the anticipated likely range of the physical circumstances. It produces a region with similar clouds and comparable covering fractions in spite of the enormous differences of the luminosity, accretion rates, etc.

The purpose of this paper is to consider the fate of the gas ejected from the accretion disk in course of the star-disk collision.² We shall argue that the wakes of the stars as they emerge following an encounter with the disk have the 'right stuff' to give rise to the BLR clouds.

STAR-DISK COLLISIONS

We consider a central black hole of mass $10^8 M_\odot$ and a Schwarzschild radius: $R_S = 2GM/c^2 \cong 3 \times 10^{13} M_\odot \text{ cm}$, surrounded by a disk with a mass $M_D \sim 10^4 - 10^5 M_\odot$ extending out to the radius $R_D \sim 10^3 - 10^4 R_S$. The typical surface density of the disk is $\sigma \sim 10^4 - 10^5 \text{ g/cm}^2$. We shall moreover assume that the disk is relatively thin, so that its height to radius ratio, h/r , may be a fraction of 10^{-2} near $10^3 R_S$ and decrease to $\sim 10^{-3}$ at $r > 10^3 R_S$.

The disk will be located at the center of the cluster with $M \sim 10^8 M_\odot$. The dynamics of the central region of the cluster ($< R_D$) is dominated by the massive black hole. Stars follow Keplerian orbits with velocities $v_* = c\sqrt{R_S/2r} \cong 2 \times 10^8 / \sqrt{r/10^4 R_S} \text{ cm/s}$. The orbital period is typically $\tau_* = R/v_* \sim 10^2 \text{ years}$, but it may be as short as a few years for the orbits just outside the tidal radius of the hole.³ Given that $\sim 10^6 - 10^8$ stars will have orbits which intercept the disk, one expects $\sim 10^3 - 10^4$ disk-star encounters per year. While these numbers may vary depending on the assumed parameters of the disk and of the cluster, it would be hard to make star-disk collisions less than a daily occurrence.

* Present address: CfA, 60 Garden St., Cambridge, MA 02138, on leave from Copernicus Center, Warsaw, Poland

Collisions occur with a Mach number given by

$$\mathcal{M} \sim (h/r)^{-1} \sim 10^2 - 10^3$$

Thus, collisions are hypersonic. Each star drills a channel with the size determined by its diameter ($\sim 10^{11}$ cm) and, in doing so, ploughs through approximately 10^{27} g of the disk material.

WAKE OF A HYPERSONIC STAR

The star-disk encounter is relatively brief. Its duration varies between $\sim 10^5$ s at small radii ($\sim 10^2 R_S$, $h/r \sim 10^{-2}$) to 10^6 s further out. The material ahead of the star is heated in a bow shock. At the disk densities ($\rho \sim 10^{-6} - 10^{-10}$ g/cm³) and the expected internal energies of $\approx 0.5(\rho v_*^2/2)$ the equilibrium pressure is dominated by the radiation, so that the temperature of the shock-heated plasma is initially given by:

$$aT_*^4 \cong \rho v_*^2/4,$$

where a is the Stefan - Boltzmann constant. This results in temperatures in the range of $10^5 - 10^6$ K. As a medium flows around the star, it forms a wake which — within a few diameters of the moving, supersonic sphere — has a universal structure schematically illustrated in Fig. 1. The velocity of the plasma in the head of the wake is approximately $v_*/\sqrt{2}$.

What happens further downstream of the hypersonically moving star is less clear, even though motion of sphere and other 'blunt bodies' through compressible fluids was studied in some detail in the fifties and sixties, mainly in the context of the re-entry of space vehicles into the atmosphere, and is summarized in reviews by Lees,⁴ and Demetriades.⁵ Following them one is led to conclude that:

- (i) In contrast to the wakes trailing slow-moving bodies ($\mathcal{M} \approx 0$) — which are usually completely laminar or completely turbulent — at higher Mach numbers the laminar-turbulent transition can occur at the same location x_T downstream from wake-shedding body.
- (ii) Increasing the Reynolds number based on the body size decreases x_T . Increase of $\mathcal{M}$ results in the increase of x_T .
- (iii) Turbulence can develop in the wake only if the Reynolds number exceeds the minimum critical value which increases with the increase of $\mathcal{M}$.
- (iv) For a fixed Mach number the critical Reynolds number, defined by $Re(x_T) = v_T x_T / \nu_T$, where the velocity and viscosity are taken in the vicinity of the transition distance x_T , appears to be a constant and is found to be $\sim 5 \times 10^4 - 10^5$ in the experiments carried out at $\mathcal{M} \sim 6$.
- (v) Experimental data indicate that the minimal Re_m , based on the size of the body, its velocity, and the viscosity of the medium, below which the flow is always laminar, is of the order of 2×10^4 at the most for 'very high $\mathcal{M}$ ' (which meant $\mathcal{M} \sim 10$ in Refs. 4-6 as compared with $\mathcal{M} \sim 10^2 - 10^3$ we are led to consider)

Reynolds numbers based on the properties of the pre-collision material d_* and v_* undoubtedly exceeds this Re_m by many orders of magnitude. However, the Reynolds number of the radiation pressure dominated hot wake computed with $T_* \sim 10^5$ K or more and the characteristic distance given by the diameter of the star is only

$$Re_{WAKE} \sim \frac{d_* v_*}{\lambda_p c} \sim 10,$$

where λ_p is the mean free path of a photon. This is much less than the critical wake Reynolds number based on the parameters for $\mathcal{M} \sim 6$ (see point (iv) above), and presumably still substantially less than the critical number for $\mathcal{M} \sim 10^2 - 10^3$.

Consequently, we expect — on the basis of the extrapolation of the phenomenological theory and laboratory results obtained at much smaller values of $\mathcal{M}$ — that the wake trailing

Fig. 1 The structure of the head of the wake behind a sphere. In the case considered here the radiation immediately behind the shock contains $\sim 10^3$ times the matter energy density and diffuses initially roughly the dimension of a stellar radius in a time corresponding to d_*/v . Therefore, the shock structure is initially diffuse, but later becomes more defined as in the figure above. Transition to turbulence is precipitated in the inner wake, but it quickly spreads out across the wake. As a result, most of the wake is turbulent, and has a self-similar character.^{1,7}

Fig. 2 Section of the disk with a wake created by a traversing star as well as a star tail above. Such star tails expand, become illuminated by the central source, and are suggested here as a candidate for the clouds responsible for the observed broad emission lines. This is a schematic drawing -- the channel drilled by the passing star would be much narrower ($d_*/h \sim 10^{-3}$).

the hypersonic star will be initially laminar. As it expands and cools its Reynolds number decreases, which precipitates the laminar-turbulent transition distance x_T behind the star. We estimate that the Reynolds number will reach the critical value at approximately $x_T \sim 10d_*$. Thus, most of the wake will be turbulent.

Laminar portion of the wake dissipates momentum only relatively slowly. Momentum transport is much faster once the turbulence is fully developed, but growth of turbulent cells is not instantaneous. Therefore, even the surface of the turbulent portion of the wake has been seen to move quite rapidly.⁶ The core of the wake is presumably still faster. Thus, as a star emerges from the disk, it is bound to be followed by a 'star tail' of the disk material which has a velocity comparable to v_* near the laminar 'head' of the wake, and falls off approximately as $(x/d_*)^{-2/3}$ in the turbulent tail, where the self-preserving solution is applicable.⁷

WAKES AND BLR CLOUDS

The hot, hypersonic material in the wake rapidly cools due to both the expansion into the cooler surrounding medium of the disk and radiative transport. It also slowed down by friction, which becomes particularly effective when the turbulence is well developed. Thus, the material trailing the star which is coming out of the disk (Fig. 2) is expected to have a spectrum of velocities and temperatures. The fastest and hottest gas will come out first. However, the bulk of the star tail that rises above the surface of the disk will come from the turbulent portion of the wake and will be both cooler and slower than the 'head'.

The emerging material with the mass $\sim 10^{26} - 10^{27}$ g will initially follow the trajectory of the star. Once above the disk surface, it will begin to expand, which will further accelerate cooling and, therefore, recombination. Its high density allows an efficient cooling, so that its temperature is likely to stabilize not far above $T \sim 10^4$ K in spite of the flux of ionizing radiation. Making the usual assumptions about the more tenuous, hot, confining medium we compute that the clouds are likely to occupy volume of $(10^{13})^3$ cm³ and have densities of $N \sim 10^9 - 10^{11}$ cm⁻³.

It is important to emphasize that, above the disk surface, the forces acting on the star and on the cloud formed from its wake are quite different. Near-Eddington photon flux will result in a $1/r^2$ repulsive force which will, in effect, decrease the value of the attractive force of the central black hole, and may result in a net repulsion for clouds with a significant neutral fractions.

The covering fraction can be computed by estimating the total number of such clouds as a function of the radius. It can be shown that the covering fraction will be dominated by the clouds close to the black hole — that is, by the tails of the stars near the radius at which their distribution becomes significantly altered by the tidal effect of the black hole or by the exchange of the momentum with the disk. Simple estimates yield covering fractions (averaged over 'the whole sky') between 0.01 and 0.5, depending on the exact extent of the clouds, cutoff of the star distribution due to tidal disruptions, etc. The covering fraction relevant for a particular observer will, of course, depend on the inclination angle.

The 'star tail model' for the BLR clouds as well as its observational consequences will be explored in more detail in the subsequent publications.

References

1. R. D. Blandford, H. Netzer, L. Woltjer, *Active Galactic Nuclei*, edited by T. J.-L. Courvoisier and M. Mayer (Springer, Berlin, 1990).
2. J. Ostriker, *Ap. J.* **273**, 99 (1983); D. Syer, C. J. Clarke, and M. J. Rees, *MNRAS* **250**, 505 (1991).
3. J. G. Hills, *Nature* **254**, 295 (1975).
4. L. Lees, *AIAA Journal* **2**, 417 (1964).
5. A. Demetriades, *AIAA Journal* **16**, 587 (1978).
6. R. E. Slattery and W. G. Clay, *Phys. Fluids* **5**, 840 (1962).
7. A. A. Townsend, in Chapter 6 of *The Structure of Turbulent Shear Flows* (second edition, Cambridge University Press, Cambridge, 1976).