Black Holes in Centers of Disk Galaxies —
— Spectroscopy with a Wide Slit

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1. Introduction

Motivated by STIS observations of more than 50 nearby galactic nuclei, we consider long-slit emission-line spectra when the slit is wider than the instrumental PSF. This practice is conventionally considered to enhance the signal-to-noise ratio (S/N) of the data at the price of what may be an insignificant loss in velocity resolution. However, when the target has arbitrarily large velocity gradients, the use of a wide slit can have more subtle effects, because the position and velocity information becomes entangled along the dispersion direction. Here we investigate these effects for emission-line spectra from gaseous disks around a central massive black hole (BH) in galaxies, but they are applicable to any objects with steep velocity gradients (*e.g.* shocks or contact discontinuities).

2. A slit wider than the PSF

For a disk in circular motion in an axisymmetric galactic potential including a massive BH, a wide slit samples off-center velocities, as well as the central rotation curve (dashed line in Fig.1, left). When the disk is observed in some emission line through a long-slit spectrograph, the pattern of intensity resembles the left panel of Fig.1, but it is modified by the geometry of spectrograph’s optics: the diffraction pattern produced by light that enters near one edge of the slit is displaced with respect to light of the same frequency that enters at the corresponding point on the other edge of the slit. Thus the difference in position across the slit is seen on the detector as an instrumental velocity offset. To reflect the light pattern on the detector, the left panel of Fig.1 has to be modified by shifting each sample line in the dispersion direction by a constant amount, different for each line. The result seen in the central panel of Fig.1 shows that in the presence of a velocity gradient across the slit, the instrumental velocity offset competes with the Doppler shifts: this offset wins at large radii, and at small radii the Doppler shifts take over. In between, both factors are of similar strength: light from all positions across the slit converges at one effective velocity, forming *the caustic*. At radii interior to the caustic, two maxima in the light distribution are present (Fig.1, right): one from the slit center (showing Keplerian rise), and one from the slit edges (passing through zero velocity at the nucleus). Thus we predict position-velocity diagrams for rotating disks to be rich in structure; the information contained in it is lost if one merely fits a Gaussian emission line profile at each radius (which is the traditional approach).
Figure 1. Left: Position-velocity diagram for the disk inclined at 60°, rotating in a potential of a 10^8 M⊙ BH plus extended density distribution $\sim R^{-1.8}$. Velocities are sampled along cuts parallel to the line of nodes, shown in the inset at upper left. Centre: The light pattern on the spectrograph’s detector (only the top half of the slit is sampled) Right: The light from entire slit integrated within the detector’s pixels.

3. A new BH mass estimator

The position of the caustic can indicate the presence, and betray the mass $M_\bullet$ of the BH. A wide slit contains many narrow slits within it, and it can provide information that otherwise would need two off-set thin slits. If the caustic occurs at a position $\alpha$ down the 2$\delta$-wide slit, then velocities at the slit center ($v_c$) and at the slit edge ($v_e$) are related by $v_c(\alpha) = v_e(\alpha) + B\delta$, where $B$ converts the plate scale in the dispersion direction to the spectrograph’s dispersion. This additional constraint allows us to recover the disk’s inclination angle $i$ and $M_\bullet$ independently, rather than $M_\bullet\sin i$. Moreover, this new method exploits an artifact at the outer edge of the BH’s sphere of influence, and therefore gives higher sensitivity to BH detection than traditional methods based on the Keplerian rise in velocity occurring inside the sphere of influence.

4. Confronting observations. Conclusions.

The most detailed long-slit spectrum of nuclear emission so far (M84, Bower et al., 1998, ApJ, 492, L111) shows two light maxima at radii close to the nucleus. Although they were interpreted as coming from two physically distinct nuclear components, the observed light pattern has the same structure as our models in Fig.1, and is caused by a wide slit. We interpret the point where the track of maximum light splits into two as the caustic, from which we estimate the disk to be inclined at 74°, and the BH mass to be $4 \times 10^8$ M⊙, smaller than that of Bower et al. by a factor of 4. BH masses derived by the traditional method may be overestimates (Maciejewski & Binney 2000, MNRAS submitted).

The finite width of the slit generates complex patterns in the spectra that can have considerable diagnostic power if they are modeled with adequate sophistication. They allowed us to develop a new method for estimating the BH mass that gives fuller information and higher sensitivity to BH detection than traditional methods.