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A Search for Offset Black Holes in LINER Galaxies

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Abstract

According to current theories of black hole formation and galaxy evolution, black holes and the AGN that they ignite do not necessarily lie at the center of the stellar distribution of their host galaxies. For example, galaxy mergers may result in binary black holes which move through the nucleus as they proceed toward coalescence. With the spatial resolution of the HST, it has become possible to search nearby galaxies on the scale of a few parsecs for offsets between the luminosity peak of the AGN, the luminosity peak of the stars, the kinematic center associated with the black hole, and the kinematic center of the stellar distribution. Here I discuss the relative locations of the photometric center and the kinematic center of a nearby bright LINER nucleus, and the instrumental effects which limit the ability to make the measurements.

1.1 Introduction

The central structure of a galaxy holds clues to its formation and evolution. Knowledge of the present structure is needed to test or inspire theories about how the spheroidal component forms, how a supermassive black hole grows (and stops growing), how the black hole affects the distribution of matter surrounding it, and how merging systems with black holes evolve. The timescales of these processes should be consistent with the observed evolution of quasars, whose energy output appears to demand the release of gravitational energy by a system containing a supermassive black hole, and the evolution of active galactic nuclei, which apparently represent minor feeding episodes for the black hole.

HST observers have made several break-throughs in determining the central structure of the spheroidal component of galaxies. They have shown that spheroids have a central light cusp (Ferrarese et al. 1994; Faber et al. 1997). Modelling of the observed power-law surface brightness profiles has shown that light density increases inward to the limiting resolution, even when the innermost surface brightness profile has the appearance of a core (Gebhardt et al. 1996). A growing body of stellar and gas kinematic observations has shown that galaxies have a supermassive black hole in the nucleus whose mass depends on the gravitational potential of the spheroidal component, as measured by its luminosity or velocity dispersion (Ferrarese et al. 2000, Gebhardt et al. 2000). As seen in M31, the black hole can be offset from both the physical center and the systemic velocity of the spheroid (Kormendy & Bender 1999). A coherent scenario is forming, in which adiabatically growing black holes in undisturbed galaxies cause a cusp to form and cause the center of the spheroid to become more circular and axisymmetric, which inhibits further growth of the black hole. Subsequent mergers produce triaxial shapes and binary black holes, which deplete the cusp by scattering stars as they wander and proceed towards coalescence (Wilson & Colbert 1995, Merritt 2000). Accurate measurements of the density profiles and the mass-to-light (M/L) profiles in spheroids, and of the exact location of the black hole, will help us refine these theories.

1.2 Galaxy Selection

NGC 3998 is a nearby S0 galaxy with an exceptionally bright nuclear emission-line disk. In my initial observations of this emission-line disk with STIS on HST, the kinematic center of the inner rotation curve, dominated by the black hole, appeared to be offset from the red photometric center by 3 pc along the major axis (Dressel & Gallagher 2001). The galaxy is symmetric photometrically, so the black hole appeared to be offset from the center of light of the bulge. This challenges current theories, in which the cusp builds up around the black hole. The unusual power of this Liner nucleus in optical line emission, radio emission, UV continuum, and X-rays, and the globally skewed neutral hydrogen distribution (Knapp et al. 1985), suggest that a merger has occurred. However, if the black hole is a wandering binary resulting from a merger, it should be scattering stars and depleting the cusp over a region large enough to observe. The continuum surface brightness distribution is a steep power-law into the center of the galaxy at HST resolution, so there is no sign of this. The importance of the implications of an offset requires further observations to see if it can be verified.

1.3 Data

I obtained new observations of the emission-line disk of NGC 3998 with STIS in April 2002. I used half-pixel along-the-slit dithering to improve the spatial resolution. This is critically important because of the tilt of the spectrum across the detector, and the spatial undersampling of the psf. For the grating and central wavelength used (G750M at 6581 Angstroms), the spectral trace drops 9 pixels as it slices across the 1024 pixel width of the detector. When the spectrum is rectified, there are therefore approximately 9 locations where integer pixel spatial shifts require no interpolation, and 9 intermediate locations where half-pixel shifts require maximal interpolation. Because the spectral image is spatially undersampled, interpolation of an unresolved source with a flat spectrum results in 9 cycles of undulations in the flux in each spectral row of the rectified image. Interpolation of a complex spectrum with a mix of unresolved and resolved components produces artifacts which are difficult or impossible to disentangle. However, the rectification can be improved substantially by interleaving two input images offset by one-half pixel in the spatial direction. It is also important to use a point source spectral image to make any necessary improvements to the spectral trace assumed in the rectification.

Figure 1.1 shows the fluxes in three adjacent rows of one of the two dithered input images in the H alpha region of the spectrum. Interpolation between the greatly different fluxes in these three rows and further adjacent rows produces the spectral rows in the rectified image. The brightest row in the rectified single image is shown in Figure 1.2 (dashed line), along with the brightest row in the rectified interleaved image (solid line), and the difference in flux between the two (solid line). In each case, the rectification was adjusted to center the red continuum beyond the [SII] lines precisely on a spectral row. The row from the better-

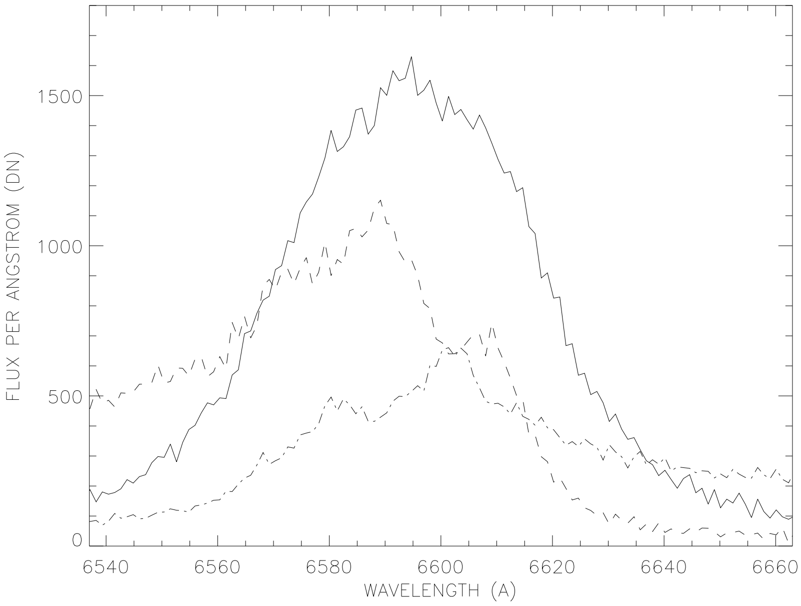

Fig. 1.1. Fluxes in 3 adjacent rows of a pre-rectified undithered spectral image of NGC 3998.

sampled rectified image has a higher flux peak and clearly different line profiles than the row from the less well sampled image. It also shows a featureless red continuum, without the undulations visible in the less well sampled product. (The figure covers 6 undulation periods, as can be seen in the difference spectrum.) Figure 1.3 shows the undersampled and better-sampled rectified spectra at a distance of 0.05 arcsec (1 row on th CCD) from the continuum peak, and their difference. Here, too much flux has spilled into the H alpha profile in the interpolation of the undersampled image. Again, the line profiles are different and will be fit or modelled differently. The interleaved image should be used to get the most reliable velocity measurements.

1.4 Results

The H alpha, [NII] 6548, 6584, and [SII] 6717, 6731 emission lines in the peak flux row of the rectified spectral images are broad and blended, as can be seen in Figure 2. Beyond this row, where lines become narrower and distinctly peaked (e.g., Figure 3), it is possible to make a first-order measurement of velocities by fitting lorentzian curves to the lines (which fit better than gaussians). I have fit the H alpha line, the [NII] pair constrained in wavelength separation, and the [SII] pair constrained in wavelength separation to get three measurements of the velocity for each spectral row in the interleaved image. Omitting the poorly constrained velocities in the central row, the resulting rotation curve is shown in Figure 1.4. Each point is the weighted average of the velocities of the three lines/pairs. The error bars show the observed dispersion in the mean, rather than model errors. The points nearest the center are being pulled toward each other by the unavoidable smearing by the

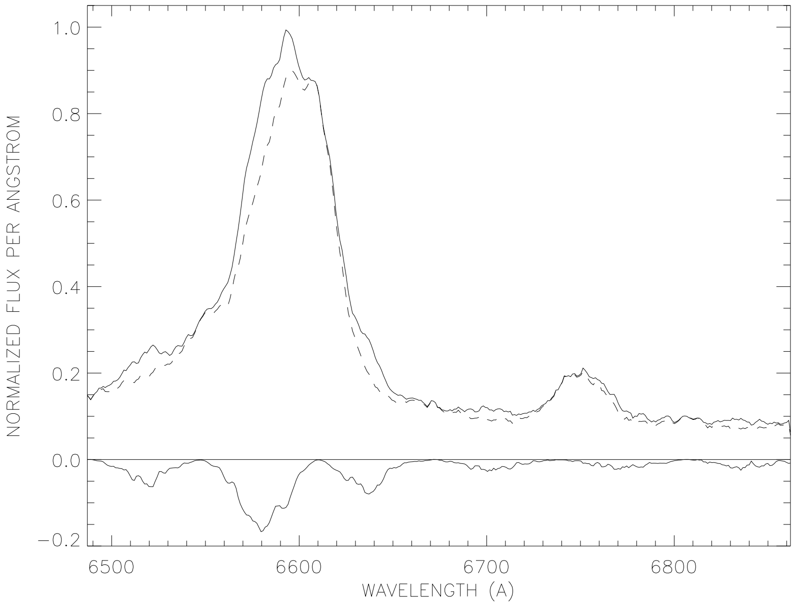

Fig. 1.2. Peak row in rectified spectral image with (solid) and without (dashed) half pixel dither along the slit, and the difference spectrum (solid).

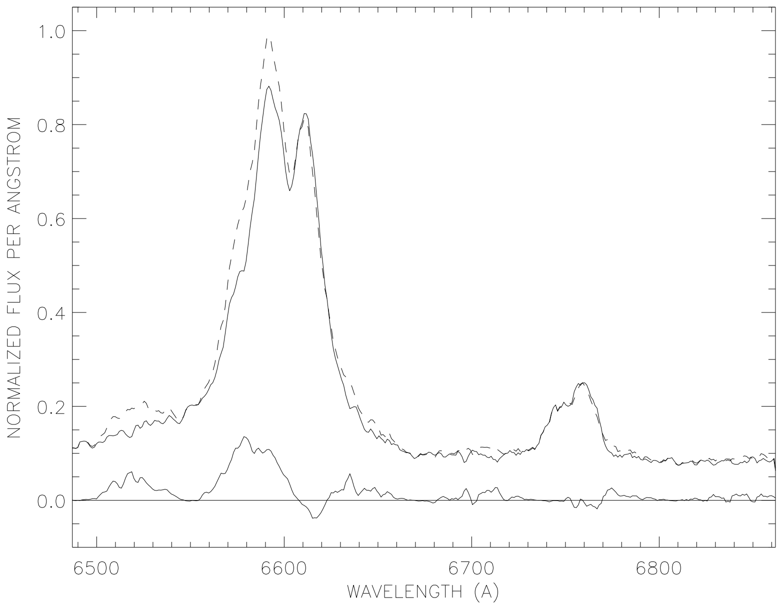

Fig. 1.3. Off-peak row in rectified spectral image with (solid) and without (dashed) half pixel dither along the slit, and the difference spectrum (solid).

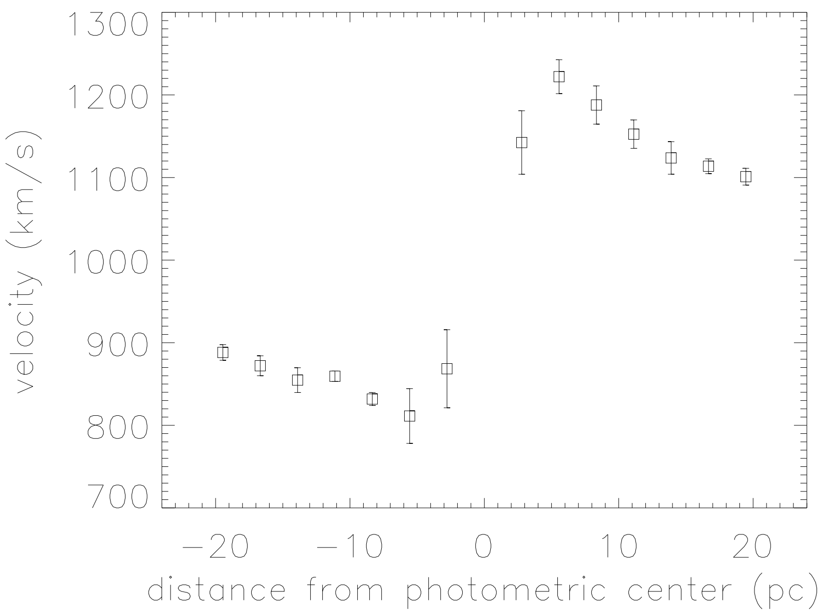

Fig. 1.4. Rotation curve from the dithered spectral image.

psf. Modelling of instrumental effects will improve the mass modeling, but the first-order reduction shows a rotation curve symmetric about the continuum peak. There is thus no evidence at this stage of the analysis for an offset between the kinematic and photometric centers in this galaxy.

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