The Central Engine of Active Galactic Nuclei
ASP Conference Series, Vol. 373, 2007
L. C. Ho and J.-M. Wang

Results from the Search for Tidal Disruption Flares in the *GALEX* Deep Imaging Survey

Suvi Gezari

California Institute of Technology, MC 405-47, Pasadena, CA 91125

Abstract. A supermassive black hole in the nucleus of a galaxy will be revealed when a star passes close enough to be torn apart by tidal forces and a UV/X-ray flare is emitted by the stream of stellar debris that plunges into the black hole. We initiated a program to take advantage of the UV sensitivity, large volume, and temporal sampling of the *Galaxy Evolution Explorer* (*GALEX*) Deep Imaging Survey to search for stellar disruptions in the nuclei of galaxies over a large range of redshifts. Here we present the detection of a luminous UV flare from a quiescent galaxy with the properties of a tidal disruption event.

1. Introduction

Dynamical studies of nearby galaxies show that all galaxies with a bulge host a supermassive black hole in their nucleus (Magorrian et al. 1998). Stellar dynamical models (Magorrian & Tremaine 1999; Wang & Merritt 2004) predict that once every 10^4–10^5 yr the orbit of a star in the nucleus of a galaxy will pass within the tidal disruption radius of its central supermassive black hole, $R_T \approx R_*(M_{\rm BH}/M_*)^{1/3}$, and the star will be disrupted. A stellar disruption results in a flare of electromagnetic radiation (Frank & Rees 1976; Lidskii & Ozernoi 1979) as the bound fraction of the stellar debris, $\lesssim 0.5M_*$ (Rees 1988; Ayal et al. 2000), falls back onto the black hole and is accreted. The characteristic temperature of the flare peaks in the extreme-UV (Ulmer 1999), and has a characteristic $(t - t_D)^{-5/3}$ decay, where t_D is the time of the disruption (Phinney 1989; Evans & Kochanek 1989). There is a critical black hole mass above which R_T is smaller than the Schwarzschild radius (R_s), and the star is swallowed whole without disruption (Hills 1975). For a solar-type star, $M_{\rm crit} \sim 10^8 {\rm M}_\odot$. The luminosity and decay of a tidal disruption flare is dependent on the mass and spin of the central black hole, and can be used to directly probe dormant black holes in galaxies for which the sphere of influence of the black hole ($R_{\rm sph} = GM_{\rm BH}/\sigma_*^2$) is unresolved, and a dynamical measurement of the black hole mass is not possible.

The most unambiguous cases for a stellar disruption occur from host galaxies with no evidence of an active galactic nucleus (AGN) for which an upward fluctuation in the accretion rate could also explain a luminous UV/X-ray flare. A UV flare from the nucleus of the elliptical galaxy NGC 4552 was proposed to be the result of the tidal stripping of a stellar atmosphere (Renzini et al. 1995); however, the possible presence of a persistent, low-luminosity AGN detected in hard X-rays (Xu et al. 2005) makes this interpretation uncertain. The *ROSAT* All-Sky survey conducted in 1990–1991 sampled hundreds of thousands of galaxies in the soft X-ray band, and detected luminous ($10^{42} - 10^{44}$ ergs s^{-1}), soft [$T_{\rm bb} = (6-12) \times 10^5$ K] X-ray flares from several galaxies with no previous evidence for AGN activity, and with a flare rate of $\sim 1 \times 10^{-5}$ yr^{-1} per galaxy (Donley et al. 2002), that is consistent with the theoretical stellar disruption rate. A decade later, follow-up *Chandra* and *XMM-Newton* observations of three of the galaxies demonstrated that they had faded by factors of $240-6000$, consistent with the $(t-t_D)^{-5/3}$ decay of a tidal disruption flare (Komossa et al. 2004; Halpern et al. 2004). Follow-up *HST* STIS narrow-slit spectroscopy confirmed two of the galaxies as inactive, qualifying them as the most convincing hosts of a tidal disruption event (Gezari et al. 2003). The *ROSAT* flare with the best sampled light curve was successfully modeled as the tidal disruption of a brown dwarf or planet (Li et al. 2002), although its host galaxy was subsequently found to have a low-luminosity Seyfert nucleus (Gezari et al. 2003).

2. Searching for Flares with *GALEX*

The DIS covers 80 deg^2 of sky in the far-ultraviolet (FUV; $\lambda = 1344-1786$ Å) and near-ultraviolet (NUV; $\lambda = 1771-2831$ Å) with a total exposure time of 30–150 ks, that is accumulated in ~ 1.5 ks eclipses (when the satellite's 98.6 minute orbit is in the shadow of the Earth). Due to target visibility and mission planning constraints, some DIS fields are observed over a baseline of 2–4 years to complete the total exposure time. This large range in cadence of the observations allows us to probe variability on timescales from hours to years. We coadd eclipses into yearly epochs, and compare catalog aperture magnitudes to search for UV variable sources that vary above 5 σ, where σ is the dispersion in Δmag due to photometric errors as a function of magnitude. Optical matches to the 5 σ variable UV sources were found, and hosts with the colors and morphology of a star or quasar were rejected. The remaining candidates were followed up with target-of-opportunity optical spectroscopy to select quiescent galaxy hosts.

3. UV Detection of a Tidal Disruption Flare

Here we report a transient UV source from an early-type galaxy at $z = 0.3968$, with no evidence of a Seyfert nucleus, recently published in Gezari et al. (2006). Figure 1 shows its detailed NUV+FUV light curve. Archival All-Wavelength Extended Groth Strip Survey (AEGIS; Davis et al. 2007) 50 ks *Chandra* (0.3 – 10 keV) observations on 2005 April 6 and 7 detected an extremely soft X-ray source that appeared on the second day of the observations, with 10 photons with energies between 0.3 and 0.8 keV, indicating a spectral slope, $f_E \propto E^{-\Gamma}$, of $\Gamma = 7 \pm 2$ (reduced $\chi^2 = 0.92$), for a column density of neutral hydrogen fixed to the Galactic value. No source was detected in the following 50 ks *Chandra* observations on 2005 September 20 and 23. Figure 1 also shows the AEGIS *H*ST ACS optical image with the UV and X-ray positions overplotted, and the AEGIS Keck DEIMOS optical spectrum from the DEEP2 survey of the host galaxy taken on 2005 March 9. CFHTLS variability monitoring data from 2005 January to June show no detection of a variable optical source in the galaxy, with up to 5 observations per month with a sensitivity of $m_{\rm lim} = 25$ mag. The flare is most probably not due to AGN activity because it displays (1) no optical variability, (2) no broad emission lines, (3) a soft X-ray spectrum with no hard

X-ray component, and (4) an early-type galaxy spectrum with possible narrow [O III] emission with a high [O III]/$L_{\rm X}$ ratio characteristic of star formation. In addition, a SN or GRB origin is unlikely because of the high UV/optical ratio.

The spectral energy distribution (SED) of the flare from optical to X-rays on 2005 April 7 is best fit with a blackbody with a rest-frame $T_{\rm bb} = 4.9 \times 10^5$ K, which for $L_{\nu_e=(1+z)\nu_o} = f_{\nu_o}(4\pi d_L^2)/(1+z)$, corresponds to $R_{\rm bb} = 6.2 \times 10^{12}$ cm and $L_{\rm bol} = 1.2 \times 10^{45}$ ergs s^{-1}. The steep Wein's tail of the blackbody curve is consistent with the extremely soft spectral slope of the X-ray source. However, since the X-ray flux varies on a short timescale, and only appears above the detection threshold for part of the observations, we consider this fit an upper limit to $T_{\rm bb}$ for the duration of the flare. The lowest $T_{\rm bb}$ that is consistent with the UV flux densities and the optical upper limits is $\sim 1 \times 10^5$ K, which corresponds to $R_{\rm bb} = 1.6 \times 10^{13}$ cm and $L_{\rm bol} = 1.3 \times 10^{43}$ ergs s^{-1}. This range of temperatures and luminosities is in excellent agreement with the theoretical predictions for a tidal disruption flare.

4. Conclusions

The *GALEX* DIS has proven to be a promising survey for detecting stellar disruption events so far. With a larger sample of tidal disruption flares, we can begin to measure the distribution of masses and spins of black holes in the nuclei of normal galaxies as a function of redshift, unbiased by the minority of galaxies that are AGNs.

References

Ayal, S., Livio, M., & Piran, T. 2000, ApJ, 545,772
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Davis, M., et al. 2007, ApJ, submitted
Donley, J. L., Brandt, W. N., Eracleous, M. J., & Boller, Th. 2002, AJ, 124, 1308
Evans, C. R., & Kochanek, C. S. 1989, ApJ, 346, L13
Frank, J., & Rees, M. J. 1976, MNRAS, 176, 633
Gezari, S., Halpern, J. P., Komossa, S., Grupe, D., & Leighly, K. M. 2003, ApJ, 592, 42
Gezari, S., et al. 2006, ApJ, 653, L25
Halpern, J. P., Gezari, S., & Komossa, S. 2004, ApJ, 604, 572
Hills, J. G. 1975, Nature, 254, 295
Komossa, S., et al. 2004, ApJ, 603, L17
Li, L-X., Narayan, R., & Menou, K. 2002, ApJ, 576, 753
Lidskii, V. V., & Ozernoi, L. M. 1979, Soviet Astron. Lett., 5, 16
Magorrian, J., & Tremaine, S. 1999, MNRAS, 309, 447
Magorrian, J., et al. 1998, AJ, 115, 2285
Moran, S. M., et al. 2005, ApJ, 634, 977
Phinney, E. S. 1989, in IAU Symp. 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 543
Rees, M. J. 1988, Nature, 333, 523
Renzini, A., et al. 1995, Nature, 378, 39
Simard, L. 1998, in Astronomical Data Analysis Software Systems VII, ed. R., Albrecht, R. N. Hook & H. A. Bushouse (San Francisco: ASP), 108
Ulmer, A. 1999, ApJ, 514, 180
Wang, J., & Merritt, D. 2004, ApJ, 600, 149
Xu, Y., et al. 2005, ApJ, 631, 809

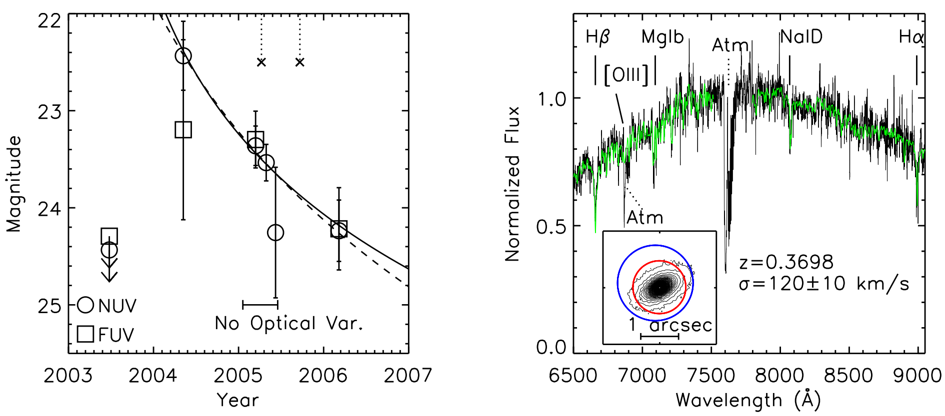

Figure 1. *GALEX* light curve in the FUV ($\lambda_{\rm eff}$ = 1528 Å) and NUV ($\lambda_{\rm eff}$ = 2271 Å). Error bars show 68% confidence intervals and arrows show 95% confidence upper limits based on Bayesian statistics. For the later observations in 2005 the FUV detector was temporarily not operational. The least-squares fit to the NUV light curve with a $(t - t_D)^{-5/3}$ decay is shown with a thick solid line, yielding a best-fit time of disruption $t_D = 2003.3$, with a 1 σ error of 0.2 yr. The least-squares fit to the NUV light curve with the power-law index, $(t - t_D)^{-n}$, and t_D allowed to vary is shown with a dashed line, with $t_D = 2002 \pm 2$ and $n = 3 \pm 2$. Dotted lines with an X indicate times of two sets of 100 ks *Chandra* 0.3 – 10 keV observations. An extremely soft X-ray source was detected during the first set observations, and no source was detected in the second set of observations. CFHTLS monitoring data from 2005 January to June in g ($\lambda_{\rm eff}$ = 4763 Å), r ($\lambda_{\rm eff}$ = 6174 Å), i ($\lambda_{\rm eff}$ = 7619 Å), and z ($\lambda_{\rm eff}$ = 8847 Å), with $m_{\rm lim}$ = 25 mag, detect no variable optical source during the UV flare. *Image:* AEGIS *HST* ACS *I*-band image ($\lambda_{\rm eff}$ = 8140 Å) of the galaxy host with the *GALEX* 1″ position error circle of the UV flare and the *Chandra* 0.″7 position error circle of the soft X-ray source, with a 1″ systematic astrometry correction applied to the *Chandra* position measured from the shift of the *Chandra* astrometry with respect to ACS for a nearby star. *Spectrum:* AEGIS Keck DEIMOS spectrum from the DEEP2 survey of the galaxy host obtained on 2005 March 9, smoothed by 6 pixels (∼2 Å), and not corrected for the instrumental response. The spectrum shows strong stellar absorption lines typical of an early-type galaxy, with a marginal detection of narrow [O III] λ5007 line emission. The best-fitting Bruzual-Charlot early-type galaxy template (Bruzual & Charlot 2003) scaled to the continuum of the spectrum is overplotted.