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Self-organized Criticality with Data from MCG-6-30-15?

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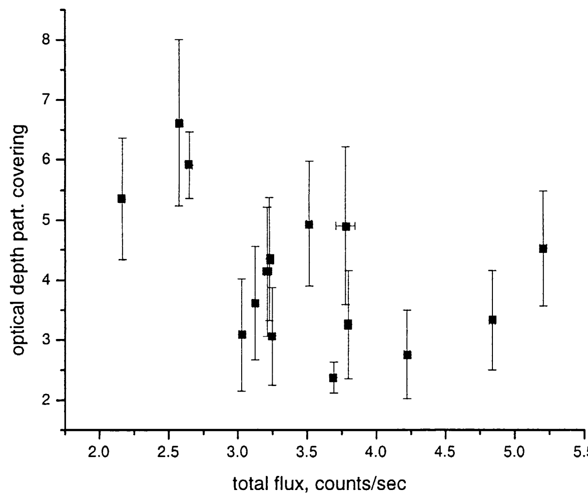
Abstract. We explain why compact sources are nonlinear and investigate the nonlinearity of MCG-6-30-15. We argue that the central engine of this Seyfert nucleus is compact and show that it exhibits a specific nonlinear behavior similar to that of a system in a critically self-organized state.

The central engines of active galactic nuclei, galactic black-hole candidates, and gamma-ray bursters pack enough energy into a small region of space to create pairs and are therefore considered "compact" (e.g., see Fabian 1992). Compact sources are highly unstable to small perturbations (Guilbert & Rees 1988), and the effectiveness of energy extraction by the perturbations is highly dependent on the compactness (Sivron 1998, hereafter S98). The yield of energy extraction of the next perturbation therefore depends on the previous perturbation. This dependence on history is typical for nonlinear, dynamical systems.

In noncompact sources, energy losses restrain nonlinear effects, and, in high-compactness sources, the situation becomes chaotic. Marginally compact sources, such as near-Eddington sources, quickly evolve to a near-critical state—self-organized criticality (SOC).

The Seyfert 1 nucleus of MCG-6-30-15 was chosen for this study because it was proven to be compact by the presence of a gravitationally red-shifted Fe K_α emission line (Tanaka 1995) and a high overall luminosity (e.g., Lee et al. 1998). MCG-6-30-15 also exhibited a $1/f^{1.4}$ X-ray power spectrum, a necessary but insufficient condition for SOC (see Yaqoob et al. 1998; Mineshige, Takeuchi, & Nishimori 1994). To figure out if the source is in an SOC state, it is also useful to look for correlation between observed events in a time series (Kaplan & Glass 1995; Vio et al. 1992; Leighly & Obrien 1997).

To verify SOC, the time series of different spectral components from the source was analyzed. The time-series results discussed below are for a power-law



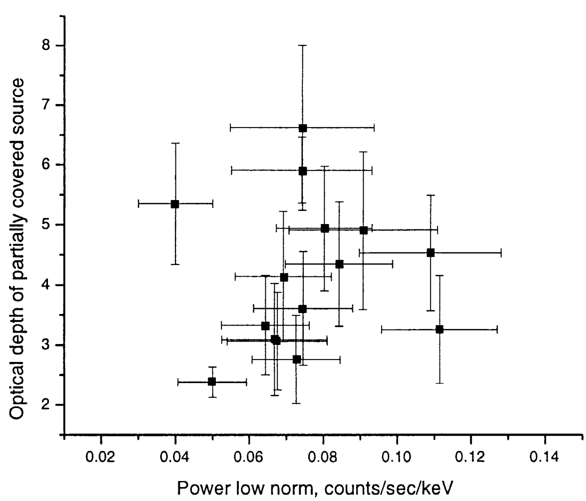


Figure 1. Correlation between the optical depth and flux (top) and the optical depth and power-law norm (bottom).

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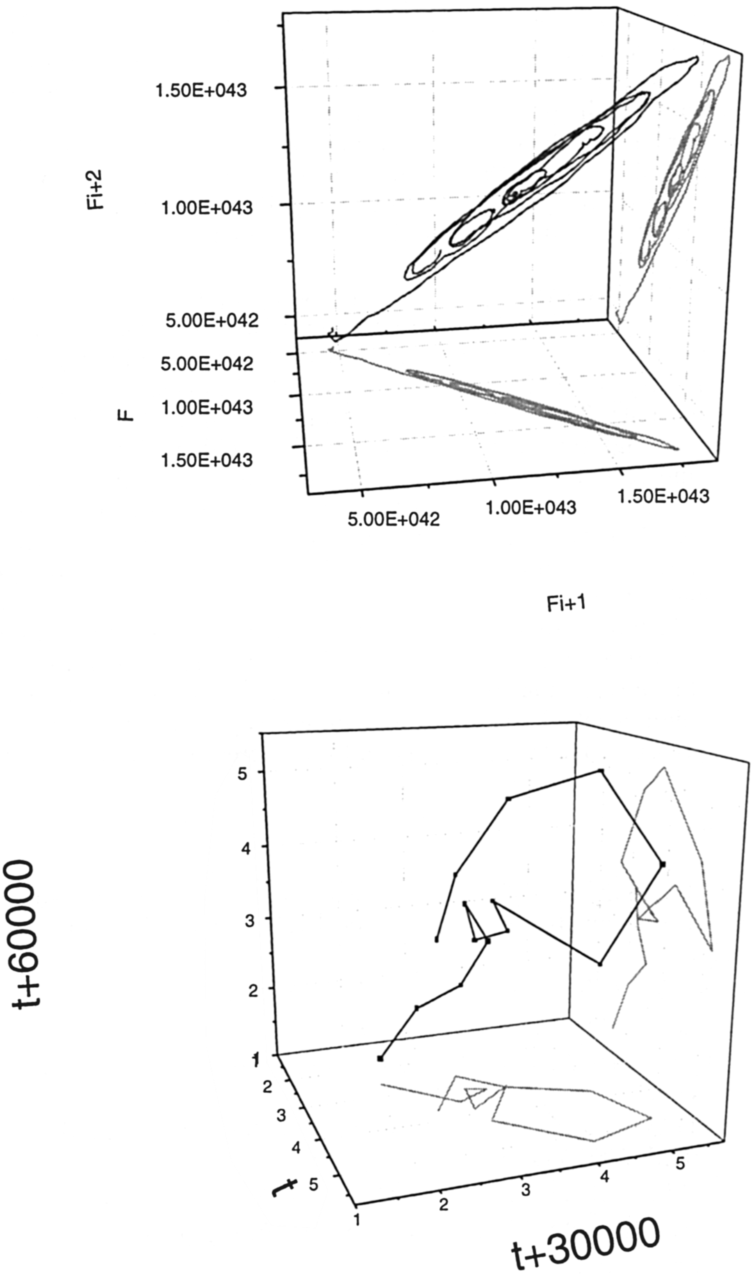

Figure 2. Trajectory in phase space for the S98 simulation (top) and the 1994 observation of MCG-6-30-15 (bottom).

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line-emission, Compton-reflecting system partially covered by a warm absorber. We analyzed X-ray data from a 4-day ASCA observation in 1994 of MCG-6-30-15 with standard near-sky background subtraction. Both SIS and GIS detectors were used, and the light curve was separated into 16 paths of nearly equal intervals from which spectra were obtained.

In Figure 1, we show the correlation between the total flux of the source and the optical depth of the warm absorber (top), and the power-law norm (bottom). The total flux from the source significantly increases just before the optical depth of the warm absorber is at its maximum. This should be expected in an SOC source.

Figure 2 shows the trajectory in phase space for the simulated compact source for S98 (top) and the current observations (bottom). The trajectory evolves into a semistable, Lorenz-like feature, which implies that the cellular automaton (CA) for the simulation is roughly the equivalent of a set of nonlinear, coupled equations. The curve on the bottom has similar attributes, but it does not contain enough information to quantitatively compare it with the SOC CA. There are indications of a "kink" of the segment that includes points 5–8 on the curve. That kink would make the return map more complicated, and the equation describing that situation will include an additional free parameter. The additional parameter implies that either the compact source is not spherical, or an additional variable, e.g., $\dot{m}$, is independent (Sivron, in preparation).

The main limitation of this investigation is the low signal-to-noise ratio for *all* spectral features, which limits the number of points in the time series. Analysis of RXTE observations of this source is under way (Sivron, in preparation). *Chandra*'s high spectral resolution and uninterrupted observation has a better chance of proving that this source is an SOC system (Jerius et al. 1997).

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