Timing analysis of AGN with MAXI data

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ABSTRACT

We performed a timing analysis on the 4-years X-ray light curves of several Active Galactic Nuclei (AGNs) obtained with the Gas Slit Camera (GSC) aboard the Monitor of All-sky X-ray Image (MAXI) at three energy bands (2-4 keV, 4-10 keV and 10-20 keV). The sensitivity of the MAXI allows us to conduct timing analysis of AGN. In order to evaluate correlations for unevenly sampled light curve, we employed a Discrete Correlation Function (DCF) analysis on the light curves. Here we present examples of results of the lag analysis, and from the above timing analysis, we successfully detected ”soft lag” in Centaurus A.

Key words: galaxies: active – X-rays: galaxies: variability

1. Introduction

The active galactic nuclei (AGNs) are the very blight cores of galaxies, and the luminosity of the core is rather higher than that of the entire galaxy. Currently the bright cores are believed to be supermassive black holes lying on the center of galaxies with a typical mass of \(10^8\) (M.J.Rees 1984) and the observed enormous energy released from the central core is explained by the gravitational energy of accreting medium (e.g. Zel’dovich & Novikov 1964). At this moment the radiation mechanism of AGNs is still unclear and is the one of the most intriguing issue of the high-energy astrophysics.

Centaurus A (Cen A) is the nearest radio galaxy from our galaxy and is known as the brightest AGNs in the hard X-ray energy band (Tueller et al. 2008), therefore Cen A is the most studied object unambiguously. Despite the astronomer’s efforts, however, origin of the X-ray radiation from Cen A is still unclear.

In this paper, we present several results of timing analysis employing the Discrete Correlation Function method utilizing the publicly-released light curves of MAXI. Especially we focused on the Cen A that shows \(\sim 10\) days long time lag between hard band and soft band. Finally we briefly discuss the interpretation of this phenomena.

2. Correlation analysis

2.1. Discrete Correlation Function Method

The Discrete Correlation Function (DCF) was introduced by Edelson and Krolik (1988). This method provides the correlation between two unevenly sampled time-series data as a function of time lag. First, we calculate the set of un-binned discrete correlations (UCDF) for all measured pairs \((a_i, b_j)\) defined as follows:

\[
UDCF_{ij} = \frac{(a_i - \overline{a})(b_j - \overline{b})}{\sqrt{(\sigma_a^2 + \sigma_b^2)(\sigma_a^2 + \sigma_b^2)}},
\]

where \(\overline{a}\) and \(\overline{b}\) are the means, \(\sigma_a\) and \(\sigma_b\) are the standard deviations, and \(e_a\), \(e_b\) are the measurement errors of data sets for \(a\) and \(b\), respectively. Each of \(UDCF_{ij}\) is associated with the pairwise lag \(\Delta t_{ij} = t_j - t_i\). Then we averaged over \(M\) pairs for which \(\Delta t < \Delta t_{ij} < \Delta t_{ij} + \Delta t/2\),

\[
DCF(\tau) = \frac{1}{M} \sum UDcov(\tau)
\]

In this paper, a positive time lag indicates that the variability of soft X-rays delays with respect to that of the hard X-rays.

2.2. The results of lag analysis

We calculated DCF for 21 AGNs utilizing the MAXI public light curves, and successfully found significant cross-correlation between the light curves at two distinct energy bands from 9 object. The examples of the results are shown in Fig. 1. We can find that the NGC 2110 (Seyfert 2) shows a hard lag in 2-4 keV versus 10-20 keV.

2.3. A soft lag in Centaurus A

We used the 2-4 keV, 4-10 keV, and 10-20 keV light curve of Cen A, and calculated DCFs of these energy bands against the 2-4 keV band. Fig.2(a) shows the calculated DCF with a bin size of 2-days. Apparently a soft lag about 10 days is inferred by the peak position or the centroid of DCF. To estimate the significance of the soft lag, we examined a Cross-Correlation Peak Distribution (CCPD) by running Monte-Carlo simulations known as...
ux redistribution/random subset selection” (FR/RSS) described in detail by Peterson et al. (1998) and Raiteri et al. (2003). In addition, to eliminate the effect of selected bin size, we performed 2000 Monte-Carlo simulations for different bin size from 2 to 10 days, thus 18000 Monte-Carlo simulations are performed. The obtained CCPDs are plotted in the Fig.2 (b), (c), and (d). Based on the above strict data treatments, we constrained the 1σ error ranges of the soft lags, 0.7±10.8 days between 2-4 keV and 2-4 keV (consistent with zero lags), 9.1±9.9 days between 2-4 keV and 4-10 keV, and 25.8±8.3 days between 2-4 keV and 10-20 keV, respectively.

3. Discussion
Assuming the observed X-ray variation is originated in the one-zone Synchrotron Self-Compton (SSC), the detected soft lags can be explained by the cooling effect of the radiating relativistic electrons. For this assumption the typical cooling time \( t_{\text{cool}}(\gamma) \) due to synchrotron radiation and inverse Compton can be described as follows:

\[
t_{\text{cool}}(\gamma) = \frac{3m_e c^4}{4\sigma_T T(U_B + U_r)^{-1}\gamma^{-1}},
\]

where \( \sigma_T \) is the Thomson cross section, and \( U_B \) and \( U_r \) are the energy densities of magnetic field and radiation. The time lag of emission \( t_{\text{lag}} \) at \( \gamma_2 \) to emission at \( \gamma_1 \) is the time for electrons to lose energy \( \gamma_1 \rightarrow \gamma_2 \).

\[
t_{\text{lag}} = \int_{\gamma_1}^{\gamma_2} \frac{d\gamma}{\gamma} = \frac{-3m_e c}{4\sigma_T(U_B + U_r)} \int_{\gamma_1}^{\gamma_2} \frac{d\gamma}{\gamma^2}
\]

Adopting the energy ratio between the photons before and after the scatterings, 1:4²/3, the typical lag in the observer’s frame can be roughly estimated as \( t_{\text{lag}} \sim 1 \times 10^6 B^{-7/4}(E_2^{-1/4} - E_1^{-1/4}) \).

Abdo et al. (2010) tried to explain the multi-wavelength SED of Cen A with a one zone SSC model and yielded a magnetic field of the emitting region \( B \sim 6 \) G. If that is the case, the expected soft lag should be \( t_{\text{lag}} \sim 0.1 \) days that is apparently inconsistent with the observed soft lag. This inconsistency may imply that the X-rays radiation from Cen A and its variability cannot be explained by a simple one zone SSC model.

References
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