Day 4:

Irregular and Aperiodic Changes

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Variability in Active Galactic Nuclei

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Invited Talk

Abstract. This talk explored variability in active galactic nuclei (AGN) for a variety of scales across the time domain. From billion-year-scale intermittency to a quasi-periodic oscillation signal with a period of one hour, time-varying signals offer insights into a myriad of complex processes driven by the AGN central engine. Athough the era of time-domain observations of AGN across the spectrum has but just begun, already observations reveal the rich detail of phenomena associated with actively accreting black holes which challenge theoretical models.

An active galactic nucleus (a.k.a. AGN, Seyfert, quasar, etc.) is an accreting supermassive black hole (BH). A jet may or may not be present. Accreting stellar-mass black holes are well-studied in our Galaxy, and it can be instructive to compare the two cases. Stellar-mass black holes are observed as X-ray binaries (XRBs), where the BH accretes material from a companion star. The hot accretion-disk emission peaks in X-rays. In contrast, supermassive black holes have relatively cooler disks, peaking in the rest-frame UV. In both cases a jet may be produced by relativistic particles collimated by magnetic fields and ejected along a single axis.

1. Intermittency in AGN

Owing to the smaller mass of the BH in an X-ray binary, the associated time-scales are proportionally smaller and transient phenomena such as the formation and cessation of jets, quasi-periodic oscillations and disk variability are easily observed on human time-frames. For example, in XRBs, jets are observed to arise or vanish as a function of accretion state. In AGN, the relevant timescales are $\sim10^7$–10^8 years, so the analogous transitions must be studied in large statistical samples. Nevertheless, some direct evidence of intermittency of AGN on long time-scales has been seen. For example, in the class of double-double radio galaxies (DDRGs), or X-shaped radio galaxies, discontinuous or cross-shaped radio emission is observed which is interpreted as due to the jet switching on and off. Another example is the case of Perseus A, a powerful radio galaxy at the centre of a massive cluster. The hot X-ray gas surrounding Perseus A shows distinct ripples around radio bubbles, evidence that its jet has been intermittently heating the cluster gas. In all of these examples, the inferred time-scale is on the order of 10^7–10^8 years, as expected if AGN behave as scaled-up accreting stellar-mass black holes.

2. Quasi-Periodic Oscillations

The X-ray power spectra of AGN and XRBs show a characteristic broken power law, with the break frequency scaling as the BH mass. X-ray binaries are also known for showing quasi-periodic oscillations (QPOs) in their light curves. The origin of these QPOs is not definitively understood, with a multitude of theoretical models proposed for their explanation. In general, they are thought to arise from some disturbance in the disk, with the frequency related to one of the disk dynamical, thermal, or other time-scales. The search for QPOs in AGN has been frustratingly difficult, with many claimed QPOs that are ultimately deemed statistically insignificant. There is one exception, a clear detection (5σ) of a one-hour period in the AGN RE J1034+396. This source is a high accretion-rate (possibly super-Eddington) narrow-line Seyfert 1. It is unknown why it has shown a QPO when so many others have not. Further study has revealed that the QPO was transient—it has not returned since the original observation. Long periods of decades or more have been searched for other sources in archives of historical observations; however, the significance of periodicity thus detected must remain low, as few cycles have ever been observed, and the number of historical observations of a given source is often sparse.

3. Measuring Black-Hole Masses

Time-domain studies of AGN prove very useful for determining BH masses from X-ray variability. BH masses in AGN are difficult to measure owing to the bright point source near the BH. Existing methods tend to rely on measurements of broad emission-line gas or invoke empirical black-hole–galaxy relations for narrow-line AGN. However, those relations may not necessarily hold for obscured AGN. The power spectra of AGN and XRBs are similar, and are characterized by a broken power-law with the break frequency proportional to the BH mass. However, measuring the X-ray power spectrum of AGN is very difficult owing to their low count rates. Alternatively, to determine the break frequency even for low-quality light curves for distant or less-luminous sources one can exploit the fact that the normalized excess variance of the light curve is equivalent to the integral under the high-frequency side of the broken power-law. A project that I carried out with James Kim successfully recovered known BH masses from AGN light curves for a small test sample, promising well for future studies of AGN in large surveys.

4. Blazar Observations with Fermi

One of the most recent advances in time-domain astrophysics came with the launch in 2008 of the Fermi gamma-ray space telescope. Fermi images the entire sky once every 3 hours, producing unprecedented coverage of transient and variable phenomena. This is central for studying blazars—relativistic jets from AGN which lie along the line of sight. These highly variable sources emit across the electromagnetic spectrum; the low-energy part of the SED is caused by synchrotron radiation from relativistic electrons in the jet, the high-energy (gamma-ray) peak mainly caused by inverse Compton scattering of ambient and synchrotron photons off those electrons. Numerous multi-wavelength campaigns, from radio to gamma-rays, have been carried out to image blazars synchronously, with results that show correlations between low and high energies (confirming the inverse Compton hypothesis); they link ejection of radio knots with large gamma-ray flares and changes in polarization (revealing the radio core to be a standing shock in the jet), and detect underlying disk emission from colour-magnitude relations. Unexpected phenomena have also been observed, such as a possible disk–jet connection related to changes in accretion state, and hysteresis in the spectral slope during flares.

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