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Variability of Active Galactic Nuclei

Variability studies have been essential in understanding the physics of Active Galactic Nuclei, AGN, because the size of the region emitting the enormous amount of energy characteristic of AGN is too small to be resolved even with existing or planned optical/infrared (IR) interferometers.

AGN emit a continuuum radiation coming from the vicinity of the black hole. They also emit intense and broad emission lines originating in fast moving gas clouds located in a small region around the continuuum source, the broad line region or BLR.

The flux level of the continuum and the intensity of the spectral emission lines emitted by AGN undergo variations on time scales ranging from hours to years depending on the energy range and on the intrinsic luminosity of the AGN.
When the flux emitted by a source of energy varies significantly (say by a factor 2) with a time scale t this flux variation sets a limit to the size R of the emitting region such that $R \leq ct$. In AGN the combination of the enormous amount of energy emitted and the very small size of the emission regions set by the short variability time scale, is not compatible with the energy being produced by normal stellar processes. The most popular model for the energy production in AGN and the basis of the current paradigm is that AGN/Quasars are powered by accretion of matter onto a supermassive black hole.

The flux variations are in general faster at high energies (Fig.1), and the time necessary for the flux to double (also called doubling time) tends to be longer in intrinsically brighter objects. The time scales and the correlations and delays between the variations of the continuum flux and of the various spectral line intensities provide information on the nature of the physical processes emitting the lines and the continuum, and on the location of the regions from which they originate.

The term AGN is used here regardless of redshift and luminosity and therefore encompasses the terms Seyfert 1 and QSO or Quasar, which are often used to designate medium- and high-luminosity AGN separately. In general, there are more data and of higher quality available for Seyfert 1's than for quasars. The reason is that they are numerous and quite a few are located within 100 Mpc of the Earth and are easily observable with the current instrumentation. In contrast, quasars are rare and even the closest ones are at such large distances from us that the flux received on earth is much less than that from Seyfert 1's (there is one exception, 3C 273). In summary, the body of knowledge of AGN variability is dominated by the observations of Seyfert 1's, which have led to physical models which satisfactorily explain the observed phenomena. It remains to be investigated how these models apply to much brighter and to much fainter AGN.

The AGN that are the subject of this article are those in which the central optical, UV, and X-ray source is viewed directly and where the variations are not amplified by relativistic effects (see ACTIVE GALAXIES: OVERVIEW, UNIFIED MODEL). For the three Seyfert 1s NGC 4151, NGC 5548 and NGC 7469, large international collaborations have organized long coherent campaigns of observations, some comprising simultaneous observations in the optical, UV and X-ray ranges, producing large amounts of data of uniform quality and gathered with optimum time sampling. A number of Seyfert 1's ($\sim$ 30) have been monitored less extensively but still sufficiently to establish that the results from the best studied Seyfert 1's are representative.

Variability of the continuum flux

The electromagnetic spectrum (continuum

spectrum) of radio-quiet AGN, after subtraction of the stellar continuum emitted by the host galaxy, extends from ~1 mm to ~100 keV with a prominent broad peak in the UV–extreme UV (EUV) range and a secondary peak in the IR (see ACTIVE GALAXIES:OBSERVATIONS). The X-ray emission is dominated by a power law component (1–10 keV; $\alpha \simeq 0.9$, where $f_\nu \propto \nu^{-\alpha}$), which steepens in the hard X-ray range (>50 keV) possibly with a cutoff around 100 keV.

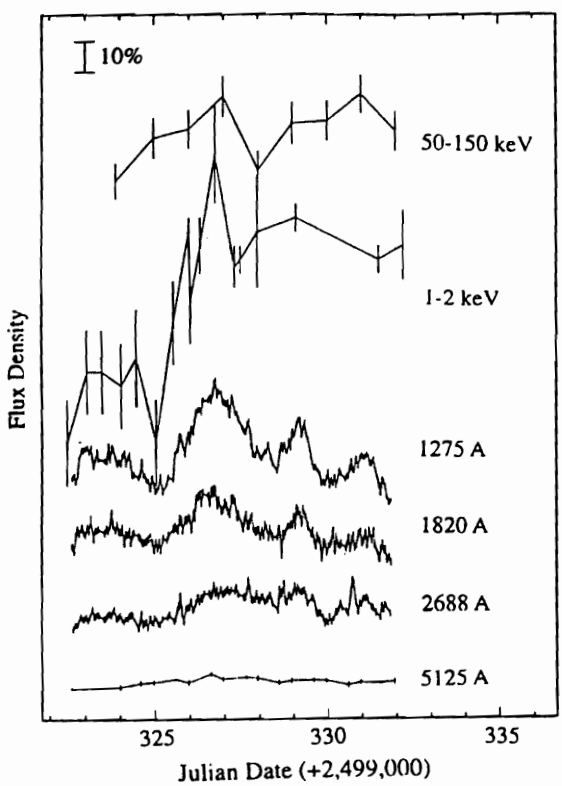

Figure 1: Variations of the continuum flux at different energies during a 10-day intensive monitoring of the AGN NGC 4151. The light curves are shifted vertically for convenience and a 10 % change is indicated by the bar.
Credit for Fig.1: R. A. Edelson et al 1996 Astrophys. Journal **470** 364

It is recalled here that in the theory of accretion disks, the accreted matter spirals in towards the center under the gravitational attraction of the black hole. The matter, however, does not flow freely. It has an internal stress (very likely of magnetic origin) whose dissipation produces heat, and also sets the time scale of the propagation of the accreted matter towards the center. Astronomers talk about the disk being heated by viscosity and about viscous time-scales, and theoreticians can calculate the energy produced by viscosity, the resulting spectrum emitted by the disk, and the time scales on which the radiation from the disk varies in response to a varying accretion rate (ACCRETION DISK). The observed spectral shape of the continuum of AGN from 1200 to 5000 Å (or 10 to 2.5 eV) is roughly consistent with thermal emission from an accretion disk. However, the variations of the UV continuum flux occur on time scales of days, weeks or months which are shorter by many orders of magnitude than the time scales expected from variations in the accretion rate. Remarkably, in NGC 4151 and in NGC 5548, the medium energy X-ray flux (2 to 10 keV) and the optical/UV flux vary simultaneously and proportionally on time scales of weeks to months (Fig.1).

Taken together, these observations suggest a model where the surface of the disk is irradiated by the central variable X-ray source.

The X-ray source variability itself is believed to be due to explosive reconnections of magnetic field lines permeating the accretion disk and the corona (the gas of hot electrons surrounding the central parts of the disk) through a phenomenon reminiscent of the solar flares in the solar corona. A significant fraction of the accretion energy is spent in this way in heating the corona.

The hot electrons transfer some of their energy to ambient UV photons (emitted by the disk) and soft X-ray photons and produce medium and hard energy X-ray photons via inverse Compton emission. This "Comptonization and reprocessing model" explains the simple correlation among X-rays and UV emission on short time scales in NGC 4151 and in NGC 5548, and also explains the average slope

of the X-ray spectrum, the high-energy cutoff and other features of AGN X-ray spectra. Considering the intricate interplay between the hot electron gas, the UV photons and the X-ray photons, it is likely that this model can also be adjusted to explain the more complex correlations between UV and X-ray found in other AGN, such as NGC 7469.

The emission line variations

A method to determine the black hole mass

Monitoring of the flux variations of the continuum and the spectral lines intensity of several Seyfert 1s have shown that the intensities of the spectral lines mimic the variations of the optical/UV continuum but with a certain time delay τ. This delay is interpreted as the time needed for the light from the central continuum source located in the immediate vicinity of the black hole to reach the gas clouds emitting the spectral lines (and located around the central continuum source) and increase or decrease the emissivity of the gas (Fig.2).

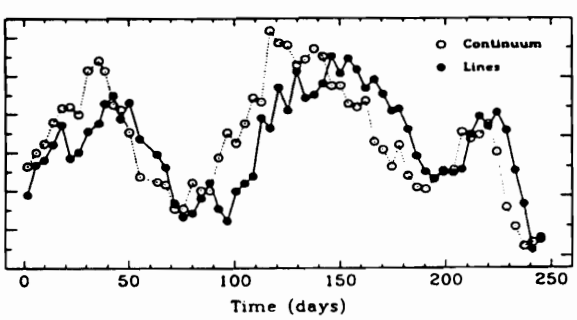

Figure 2: The UV continuum flux (open symbols) and the emission line intensities (here the sum of all the lines; dots) as a function of time, for the AGN at the center of the galaxy NGC 5548. The delay of $\sim$ 15 days between the two light curves means that the lines are formed at a distance of $\sim$ 15 light days or 5 x 10^{16} cm.
Credit for Fig.2: D. Maoz, 1997 in *Emission Lines in Active Galaxies: New Methods and Techniques* p. 138. ASP Conference Series, **113** B. M. Peterson, F.-Z. Cheng, and A. S. Wilson (eds.)

The time delay τ gives a measure of the distance $d \sim c\ \tau$ of the line emitting gas clouds from the central continuum source.

The mass of the central black hole can then be calculated (to first order) from d and from the velocity of the gas clouds measured from the width of the emission lines, assuming that the clouds' motions are orbital motions in the gravity field of the black hole. Strong support for this assumption is provided by the variability of the line profiles (see below).
This method of determining the mass of the central black hole has been applied to more than a dozen of AGN and yields values in the range a few $10^6 M_\odot$ to a few $10^8 M_\odot$.

The velocity field of the gas

One of the crucial elements contributed by variability studies is that the broadest emission lines vary with the largest amplitude and on the shortest time scale indicating that the fastest moving gas is closest to the center.

The detailed variations in line intensity and profile provide the answer to the question which is critical to the determination of the mass, as to whether the clouds are gravitationally bound to the central black hole: The line profile variations do not show the systematic effect of one wing responding before the other that would be expected for radial flows: The blue wing would be observed to vary first in the case of outward flows and spherical winds, and the red wing would be observed to vary first in the case of spherical accretion. [FOOTNOTE:Take the example of an expanding sphere of gas whose emissivity varies under the influence of the varying central continuum. A signal from the central source - for example an increase of flux - reaches all the points of the sphere simultaneously, but the first signal which we receive from the sphere originates from the part closest to us and which is in motion towards us.

We will, therefore, first observe an increase of the short wavelength part, or blue wing, of the emission line]. This, and the fact that the fastest moving gas is closest to the center, strongly suggest that the high ionization clouds are in orbital motions (chaotic or rotation motions) in the gravitional field of the black hole, with only minor components of net infall or outflow. Chaotic motions are ruled out because the gas clouds would be destroyed when crossing the accretion disk.

The most detailed result on the velocity field in the BLR comes from an intensive monitoring of the CIV line profile during "a month in the life of NGC 4151", with nearly complete 1-day sampling over a 35-day interval. The analysis of the variations in each interval of velocity in the CIV line profile shows the variations to be consistent with gravitational motions around a mass of $\sim 10^7 M_\odot$. This value agrees with that resulting from observations of the entire UV spectrum of NGC 4151 at other epochs, which show a linear relation between the response time of a line and the inverse square of the line width. Other AGN give consistent results (albeit less detailed) and it is thus concluded that the line width is primarily due to rotation. This forms the basis of the determination of the black hole mass from the response of the emission line intensities to the continuum flux variations.

The "disk and wind" model

In AGN spectra there are low-ionization lines, such as the Balmer lines and lines of FeII and MgII, and high-ionization lines (the strongest are lines of CIV, NV, HeII, SiIV). Interpretation of the observations show that the low-ionization lines come from a flat aggregate of very dense clouds ($N_e \geq 10^{11}$ cm^{-3} and total optical thickness of 10^{24} cm^{-2}) which is identified with the relatively cool part (surface temperature of 5000 K) of the accretion disk.
The high-ionization lines, in contrast, come from a comparatively more dilute medium, above and below the disk, the lines of the most highly ionized elements being the broadest. This indicates that the degree of ionization is correlated with the gas velocity (Fig.3).

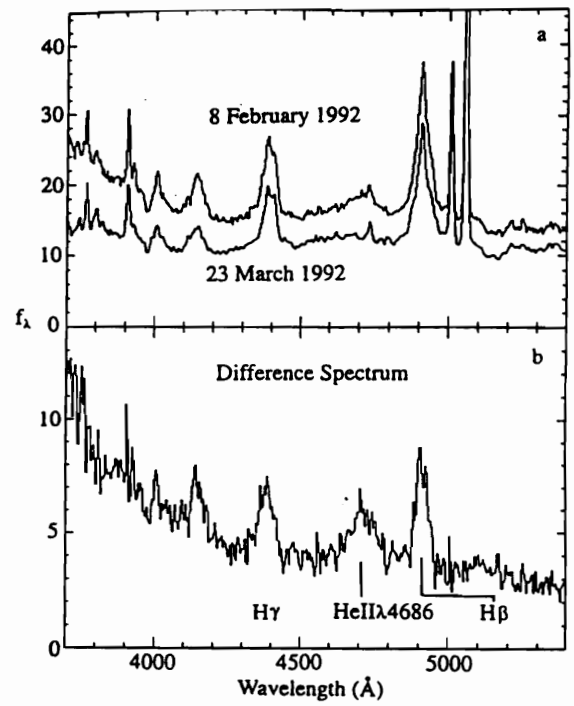

Figure 3: The variations over 44 days of the optical spectrum of the active nucleus of NGC 3783. The difference between the two spectra illustrates the large width and variability of the high ionization line of HeII as compared to the other lines. The continuum spectrum is steeper at high state, a general property of AGN. Same unit of flux on both panels, 10^{-15} erg s^{-1}cm^{-2} A^{-1} .
Credit for Fig.3: G. M. Stirpe *et al.* 1994 *Ap.J.* **425**, 609

Remarkably, the high ionization lines are not exactly at the redshift of the low ionization lines (emitted by the accretion disk), which themselves are at the host galaxy redshift. They are blueshifted (by 0 to ~1500 km s^{-1}) with respect to the disk and the host galaxy, indicating that the highly ionized gas is flowing out towards us. (By symmetry, a flow is probably moving away from us, on the other side of the disk, but is hidden from view because the disk is opaque). The combination

of rotation and outflow from the disk suggests and is consistent with a model where the high ionization lines are emitted by gas clouds emerging from the disk, still retaining a large part of the angular momentum that the gas had in the disk.

Such motions are predicted by the magneto-hydrodynamical model of accretion disks in which magnetically accelerated winds are formed from filaments pulled from the originally dense low-ionized material of the accretion disk and subjected to the intense central ionizing field. This forms a highly ionized wind above and below the disk. The physics of these phenomena, however, is complicated and many features of this promising model remain unspecified at present.

Current problems and future developments

There remain a number of questions and exciting avenues of investigation.
First, the theoretical investigation of the magneto-hydrodynamical effects which, together with the gravity field of the black hole, dominate the physics in the black hole surroundings needs to be vigorously pursued.
Second, the variability phenomenon has been best observed and is best understood in the case of the medium luminosity AGN (Total luminosity $L \sim 10^{42}$ to 10^{45} erg s^{-1}), but variability data on powerful quasars (up to 10^{49} erg s^{-1}) and on very low luminosity AGN (10^{39} erg s^{-1}) are still very few. Fortunately, the relevant observations are under way. They will make it possible to investigate the entire parameter space defined by the black hole mass and the accretion rate and to understand the specific characteristics of the accretion process in the different regions of this parameter space (e.g. advection, accretion of single stars, super-Eddington accretion rate).

Finally, although this article is focused on the directly observable variability of AGN, i.e. occuring on time scales of hours to years, it is pointed out that other variability phenomena must occur on longer time scales, 10^2, 10^6 to 10^9 years. Specially relevant to this is the recent discovery (from measurements of the velocities of stars in the nucleus of nearby galaxies) that black holes are likely to be present in the center of non-active galaxies, including our own Galaxy, with masses roughly in the same range of values as those determined from AGN investigations. A number of questions then naturally arise such as to whether AGN could be recurrent phenomena with dormant phases, and as whether they can be fuelled by gas produced through the evolution of the stars in the host galaxy or whether the accreted material always come from outside the host galaxy.

Bibliography

First inkling of the potential of variability to understanding AGN: Andrillat, Y & Souffrin, S 1968 *Astrophysical Letters* **1**,111

Hydrodynamic flows from accretion disks: Blandford, R D & Payne, D G 1982 *Monthly Notices Royal astr. Soc.* **199**, 883

Comptonization and reprocessing model: Haardt, F & Maraschi, L 1993 *Astrophys. J.* **413** 507

Assessment of the state of the field with numerous references: Ulrich M-H, Maraschi L, & Urry C M 1997 *Annual Review of Astronomy and Astrophysics* Vol **35** 445-502

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