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INFRARED AND X-RAY CONTINUUM FORMATION IN NON-BLAZAR AGN

M. de Kool
JILA, University of Colorado and NIST

Despite a large amount of theoretical effort in the last few years, there seems to be little consensus as yet on what radiation processes are responsible for the formation of the continuum radiation in non-blazar AGN, especially in the infrared (IR) and X-ray bands. In the IR the main question is whether, beside thermal emission from radiatively heated dust, a significant non-thermal (synchrotron or synchrotron self-Compton) component is present (e.g. Carleton et al. 1987). In the X-rays the main competition is between thermal models, that explain the X-ray spectrum by thermal Comptonization by a hot electron gas (see e.g. Dermer 1988 and references therein), and non-thermal models that rely on a population of non-thermal, relativistic electrons that produces the X-rays through synchrotron or relativistic Compton scattering (see e.g. Fabian et al. 1986, Lightman and Zdziarski 1987, Ghisellini 1989).

Detailed models of AGN continuum formation based on the scenarios above have met with some succes in explaining particular features of the spectrum, such as the X-ray spectral index and spectral breaks at a few MeV, but basic uncertainties about these sources, most prominently the lack of information about the geometry of the emitting regions, have prevented drawing any hard conclusions. In this paper I shall give some old and some new arguments that seem to constrain the mechanisms responsible for the continuum formation, staying as close as possible to observational facts and minimizing the number of assumptions.

THE INFRARED CONTINUUM

In my opinion the following points argue against an important non-thermal contribution to the infrared continuum of non-blazar AGN:
1) The lack of IR variability (e.g. Edelson 1987). Since in most sources the X-rays
show clear variability, it is hard to understand how the IR can be constant, since in non-thermal models both are caused by the same relativistic electron distribution.

2) The steepness of the infrared spectral slope \( (\alpha \geq 1, F_\nu \propto \nu^{-\alpha}) \) (Neugebauer et al. 1987). In non-thermal models, spectral indices \( \geq 1 \) can only be obtained if the index of the relativistic electron distribution \( (N_\gamma \propto \gamma^{-p}) \) is greater than 3. However, if this is the case most of the energy is lost by low energy \( (\gamma \sim 1) \) electrons, that cannot cool by synchrotron radiation because of self-absorption effects. If these low-\( \gamma \) electrons cool by the synchrotron self-Compton process, the energy in the Comptonized radiation has to be larger than in the original synchrotron radiation, generally leading to \( \alpha \leq 1 \) (de Kool, Begelman and Sikora 1989).

3) The steepness of the sub-mm and far infrared spectrum, in some cases \( \alpha < -2.5 \) (Chini et al. 1989). Although slopes slightly steeper than \( \nu^{5/2} \) can in principle be produced by a self-absorbed synchrotron source (de Kool and Begelman 1989a), radiative transfer effects make it unlikely that these can actually be obtained. Steep slopes are much easier to obtain from dust emission, since single temperature dust will emit a spectrum with \( F_\nu \propto \nu^{-4} \) in the far-infrared and sub-mm regions.

Arguments like the above have led several people in the last few years to the conclusion that any non-thermal contribution to the infrared continuum is negligible. Before accepting this viewpoint, however, I feel that the following questions have to be resolved.

1) The lack of dust features in the AGN continuum, especially the absence of the 10 \( \mu \text{m} \) feature (Roche et al. 1984). Almost all infrared emitting objects in our galaxy show this feature, making it hard to understand why these active galaxies do not show any. For comparison, it would be interesting to have more spectrophotometric data around 10 \( \mu \text{m} \) available for normal galaxies.

2) If the near-infrared emission is due to hot dust close to the evaporation temperature, and the optical emission is either due to starlight or an accretion disk, it is remarkable how continuous the spectrum is at the transition between these different components, around 1 \( \mu \text{m} \). One would expect that at least some AGN have a large amount of hot dust, so that the spectrum drops steeply from the near-IR to the optical. Even in a large sample such as that of Neugebauer et al. (1987) this behaviour is never observed.

3) The good correlation between the X-ray (6 keV) and infrared fluxes (e.g. Carleton et al. 1987). The correlation is very tight in the near IR (3.5 \( \mu \text{m} \)), and gets worse for longer IR wavelengths. This would seem to indicate a direct connection between the mechanism responsible for the X-ray flux, which has to be non-thermal or at least associated with a very hot plasma, and the mechanism producing the near-IR flux. A possible solution for this problem is that the hot dust is mainly heated by the active nucleus, also responsible for the X-rays, whereas the cold dust radiating at longer wavelengths is mainly heated by starlight.

THE X-RAY CONTINUUM

In the X-ray band the situation is even more unclear than in the IR, mainly because of the quality of the available data. In most cases only 2 or 3 broadband fluxes are available, and only for the brightest objects have low-resolution spectra been obtained. It can
reasonably be assumed that the continuum is shaped by one or a combination of the following processes: free-free emission or thermal Comptonization by a hot thermal plasma, or synchrotron or relativistic Comptonization by a non-thermal electron distribution. The spectral slopes as determined by the broadband fluxes are not sufficient to distinguish between these mechanisms or exclude one of them (maybe with the exception that synchrotron radiation cannot produce a spectral index $< 0.5$, which is observed in a small number of sources).

Recent results from the Ginga satellite, however, give us some hope that with better quality data we will begin to be able to constrain the emission mechanisms. These observations of the spectral variability in the Seyfert galaxies MCG 6-30-15 and NGC 4051 (Matsuoka et al. 1989) seem to imply a correlation between the 2-10 keV luminosity and the X-ray spectral index, which varies between 0.5 and 1.0. This correlation is in the sense that the spectrum steepens as the source gets brighter, and the spectrum seems to pivot around a point between 30 and 50 keV. Can this behaviour be explained by any of the radiation mechanisms mentioned above?

Unfortunately, thermal bremsstrahlung models can almost never be excluded, because the proper superposition of temperatures can explain any spectrum with $\alpha \geq 0$. We would expect, however, that for physical conditions that are reasonable for AGN, thermal Comptonization effects caused by the hot plasma will start to influence the formation of the spectrum long before free-free emission becomes important (de Kool and Begelman 1989b).

The thermal Comptonization model has big difficulties in explaining the observed behaviour. If the soft photon source is constant, as seems to be indicated by the lack of significant variability in the UV, an increase in the scattered luminosity will always be accompanied by a flattening of the spectrum. This is in contradiction with the observations.

If the X-rays are pure synchrotron radiation, the spectral slope is directly related to the slope of the relativistic electron distribution, and the steepening spectrum implies a steepening electron distribution. This can be caused by either a steepening of the injection spectrum of relativistic electrons, or by the increased saturation of the pair cascade mechanism due to the increased compactness of the source. The latter possibility is tempting, because the observed range in spectral indices is exactly as would be expected if the relativistic electrons are injected at very high energies, and the pair cascade varies from unsaturated to saturated. However, more detailed calculations show that the spectral index changes more rapidly with luminosity than can be explained by this model. This leads to the conclusion that in the synchrotron scenario, the observations indicate a change in the relativistic electron injection function with luminosity.

If we consider non-thermal relativistic Comptonization, two cases can be distinguished: the single scattering case ($\tau_{Thomson} < 1$) and the multiple scattering case ($\tau_{Thomson} > 1$). In the single scattering case the same reasoning applies as in the case of synchrotron radiation, and the change in slope has to be due to a change in the electron injection function. The multiple scattering case is very similar to thermal Comptonization, and would again lead to a flattening of the spectrum with increasing luminosity.

Thus we see that sufficiently detailed observations can indeed constrain the importance of the different physical mechanisms. For the case discussed above, we find strong
indications that the X-rays come from a non-thermal source, and that the relativistic electron injection spectrum changes with luminosity.

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MEASUREMENTS OF TILT USING A BOREHOLE TILTMETEER

Judah Lavine*
Joint Institute for Laboratory Astrophysics
National Institute of Standards and Technology and
University of Colorado, Boulder, Colorado 80309-0440

This paper describes a borehole tiltmeter based on a pair of horizontal pendulums. We have used the tiltmeter to study the elastic properties of the Yellowstone National Park region by measuring the amplitude and phase of the earth tides there. We are currently operating several of these instruments in seismically active regions of Southern California to study the usefulness of borehole tilt measurements in earthquake prediction and in measuring the distortion of the near-surface material near a fault zone.

Although many different kinds of tilt-sensors have been developed, they are often not suitable for measuring the small, long-period distortions of the earth. Tidal tilts, for example, have amplitudes of about 200 nanoradians (0.04") and periods of 12 hours or longer; secular distortions rarely exceed 1 micro-radian per year, and are often considerably smaller than this value. These effects must be measured at remote, inaccessible sites in an environment where ambient temperature and pressure cannot be controlled, where power consumption must be minimized, and where the mean time between failures must be several months or longer.

Borehole Design

We have minimized the sensitivity to environmental perturbations by installing the sensors in boreholes as shown in Figure 1. The boreholes are nominally 15 cm in diameter and 30 m deep. A carbon steel casing, 135 mm in diameter with 6-mm walls is pressed into the hole. The casing is welded into a continuous, water-tight pipe as it is inserted. The casing terminates at the bottom in a stainless steel section used to hold the tiltmeter capsule. This bottom section is 2.4 m long and 115 mm in outside diameter. It is sealed by a plate welded across the bottom. A hemispherical knob is welded to the inside of the bottom plate to support the weight of the tiltmeter capsule. At some sites we also used a second, larger diameter casing to keep the top portion of the borehole from collapsing after the drill was removed and before the primary casing could be inserted. This larger casing was 210 mm in diameter. The length of this casing varied depending on local conditions.

The casing is sealed in place by means of cement poured down to the bottom of the hole before the casing is inserted and around the sides of the casing after it is in place.

Fig. 1. Schematic diagram of the tiltmeter capsule installed in a cased borehole. All dimensions are nominal and the figure is not to scale. The detail shows one of the springs that is used to press the capsule against the side of the borehole to minimize the effect of strain-tilt coupling.

Ordinary cement can be used for 30-m boreholes. The cement is mixed somewhat thinner than normal, and can be poured around the casing by hand. This technique will not work for deeper boreholes, however, and the cement must be pumped to the bottom of the hole. Special mixes must be used to prevent the cement from separating and clogging the pipe used to carry the mixture to the bottom of the hole. The most important consideration is the balance between fine and coarse constituents of the mixture, and mixes that are easily pumped may be somewhat brittle when cured.

Although we have installed instruments in boreholes that were only 15 m deep, these instruments showed quite marked response to surface perturbations produced by changes in temperature or by rainfall. In Figure 2, we compare the response to rainfall of sensors

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*Staff Member, Time and Frequency Division, NIST.
that are installed at a depth of 15 m (VP1 and VP2) with data from an adjacent 30-m deep installation. The periodic tilts on both instruments are the earth tides; note the larger secular effects on the shallower instrument and the pronounced effect coincident with the rain.

Instrument Capsule

The instrument capsule is a 1.8 m length of stainless-steel tubing closed at the bottom and having a pair of contact points and a flat spring welded on near its top and a second pair with a second flat spring near its bottom. The top of the capsule is sealed with a cap attached by screws and containing an O-ring.

The springs press the capsule against the casing; the weight of the instrument is supported by the hemispherical knob at the bottom of the casing, but this knob does not constrain the capsule. This design is intended to minimize tilt-strain coupling due to cavity effects. When the material that was in the borehole is removed by drilling, the elastic properties of the region are modified since the edge of the borehole is now a stress-free surface. Strains in the surrounding material deform the sides of the borehole, and this deformation varies with position, especially near the bottom of the hole where there is a transition region between the modified and unmodified zones of elastic parameters. This differential motion results in apparent tilts, as points that were directly above each other are displaced by different amounts as a result of the applied strain. It can be shown that there is no cavity effect if the side of the borehole is used as a vertical reference axis for the tiltmeter, provided that the reference points are more than about one hole-diameter above the bottom. (These cavity effects are much more difficult to eliminate if the borehole is not vertical. In particular, tilt measurements in railway tunnels or mine drifts present special problems that are not easily overcome.)

The cables connecting the capsule with the surface are left slack; their weight is supported by a bracket fastened to the top of the casing.

Capsule Orientation

The capsule is usually not visible from the surface and its orientation cannot be determined by direct sighting. We use a system of light rods instead. A post is welded to the top cap of the tiltmeter with a flat side aligned with the axis of one of the sensors. A rod can be fastened to the post and is held in place by means of a trapped ball. As the capsule is lowered, additional sections of rod are added. Each section is notched and can only be attached in one orientation using a small screw. After the orientation of the topmost notch is determined using a compass and a transit, the entire series of rods is removed from the capsule by pulling upwards, thereby disconnecting the bottom rod from the post.

This method can be used to determine the azimuth of the sensors to within a few degrees. An uncertainty of only one degree is possible if great care is used and conditions are very favorable.

NBS Tilt and Rainfall

![Graph showing NBS Tilt and Rainfall](image)

Fig. 2. Tiltmeters VP1 and VP2 are installed in a 15-m borehole and tiltmeter HP2 is in a 30 m borehole. The response of the instruments to rainfall is shown. The periodic signal of all of the plots is the earth tide.

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Tilt Sensors

The tilt sensors are horizontal pendulums and the design is shown in Figure 3. A mass, M, is located at the end of a rigid beam, B. The beam is supported by three wires, W₁, W₂, and W₃. Two important features of the mechanical design are the small springs (S) incorporated into each of the wires to protect the suspension from damage due to shock or vibration and the pantograph arrangement of the suspension which makes the period and the mechanical sensitivity independent of temperature to first order. The wires are attached to the frame of the instrument at P₁, P₂ and P₃, but the diameter and stiffness of each wire are chosen so that displacements of the mass are with respect to the virtual hinge points V₁, V₂ and V₃. These hinge points lie along a line offset from the vertical by a small angle i. If the vertical axis tilts out of the plane of the paper by a small angle d, the pendulum swings out of the plane of the paper through an angle δ, where δ = d/i. If the length of the beam is L, the mass moves a distance Lδ = d(L/i). The time to reach the new equilibrium position is proportional to the period, which depends on (L/i)¹/². In our instruments, L = 10 mm and i = 2.3°. The period is 1 second, the mass moves 0.24 μm/μrad, and the displacement of the pendulum in response to a tilt is equivalent to a vertical pendulum that is 240 mm long. The mechanical amplification (relative to a simple vertical pendulum of the same length as the beam) is thus about 24.

Each instrument consists of two pendulums mounted so that their sensitive axes are perpendicular to each other. The pendulums are mounted on a small plate as shown in Figure 4, and are protected from air currents and dust by a sealed cylindrical cover. The mounting arrangement isolates the pendulums from the flexing of the hermetically sealed case due to changes in barometric pressure. The case is approximately 65 mm high and 70 mm in diameter.

Fig. 3. A horizontal pendulum. A mass M is suspended at the end of a beam B using 3 wires W₁, W₂, and W₃. The wires are attached to the vertical support at points P₁, P₂ and P₃. The pendulum rotates about three virtual pivots V₁, V₂ and V₃ which lie along a straight line offset from the vertical by a small angle i. The small springs (S) protect the suspension from damage due to shock or vibration.

Fig. 4. The mounting plate. The pendulums are mounted on the raised inner plate so as to isolate them from the flexing of the base plate produced by atmospheric pressure changes acting on the sealed case.

The base-plate is supported on a three-point mount; two of the support points are motor-driven screws. These motors are used to level the instrument after the capsule is installed. The platform has a dynamic range of about 0.1 rad (5°), and the instruments can be zeroed to about 0.1 μrad. See Figure 5.

Each pendulum is suspended between two plates separated by about 1 mm. The plates and the pendulum form two arms of a capacitance bridge; the other two arms are formed by the center-tapped secondary coil of a transformer. The area of each end-plate is about 1 cm², so that the capacitance between the pendulum and each end-plate is about 1 pf. The primary of the transformer is driven by an a.c. signal and the amplitude and phase of the signal at the center plate are measured using a phase-sensitive detector. Since the voltages on the two outer plates are equal in amplitude and opposite in phase, the voltage between the center arm and the center-tap of the drive transformer has a magnitude that is proportional to the deviation of the pendulum from the electrical mid-point of the system; the phase gives the direction of the offset. The frequency of the drive is not critical and is usually about 10 kHz. Higher drive frequencies
The sensitivity of each pendulum is measured in our laboratory using a tilt table. Successive calibrations agree to within 1% even if they are performed several years apart. Once the mechanical sensitivity of each pendulum has been determined, the gain of its amplifier is adjusted to yield the nominal overall sensitivity discussed above, and successive calibrations are then performed on the sensor-amplifier pair.

Filters and Digitizer

The outputs of the two phase-sensitive detectors are transmitted to the top of the borehole where they are low-pass filtered with a low-frequency gain of unity and using a time constant of 200 s. The voltages are then digitized with a 12-bit digitizer having a full scale range of ±10 V; the least count of the digitizer is equivalent to a tilt of about 2 nano-radians and the digitizing frequency is 10 times/hr. The data are stored in a small single-board computer at the top of the borehole and are transmitted to our laboratory once per day using dial-up telephone lines.

Power Supply

The entire tiltmeter system uses approximately 7 W. Most of this power is used by the digitizing and recording circuits. This power is provided by 12 V batteries that are continuously trickle-charged from commercial power lines. Great care is necessary to isolate the tiltmeter from the power-line ground if fluctuations in ground currents are not to be a problem. Power-line transients and large fluctuations in the input voltage are also a problem; these are quite common at remote sites and may be quite difficult to remove. At some sites, the power line transients are so large that any connection at all between the tiltmeter and the power line degrades the measurements by an unacceptably large amount. In these situations we have used a pair of batteries that are alternately charged by the power line and connected to the tiltmeter. The switch-over is made about once per hour by a series of switches that are actuated by a motor-driven cam.

Results and Discussion

A complete discussion of our results is beyond the scope of this paper, but some representative results are presented below. Since most of our work involves the measurement of long-period tilts, the diurnal and semi-diurnal components of the earth tides provide convenient signals to calibrate the instruments and to test various analysis procedures. Measurements of the amplitudes and phases of the larger tidal constituents can also provide information on the elastic parameters of the earth in the vicinity of the instrument, since they represent the elastic response of the region to a known driving potential. It is also possible that the amplitude or phase of the tides might change if a material became dilatant shortly before it fractured. This
effect, which has not been observed in field measurements, would provide a warning of imminent failure which might be useful in earthquake prediction.

Figure 6 shows a typical power spectrum obtained from a data set 28 days in length. The data were recorded using a horizontal pendulum installed at the bottom of a 30-m borehole in Boulder, Colorado. The dotted curve shows the residuals of a least-squares fit of the theoretical tidal potential to the measurements. The long-period and ter-diurnal tides were not estimated in the fitting process, and the two spectra are therefore identical at these frequencies.

The signal-to-noise ratio in the semidiurnal band, estimated by comparing the residual power to the signal power, is of the order of about 10 dB. The signal-to-noise ratio in the diurnal band is only about 20 dB because of the sensitivity of the site to the diurnal pressure and temperature fluctuations acting both directly on the instrument and indirectly through thermoelastic effects in the earth.

Measurements of the secular tilt rate may also be useful in earthquake prediction. These data are particularly difficult to interpret, since the measurements cannot be unambiguously separated from spurious tides due to drift in the instrument or in its immediate surroundings. These spurious effects often dominate long-period tilt records, with the result that long-period records obtained by two nearby nominally identical instruments often show little correlation.

In addition, many sites exhibit large annual (and 24-month period) tilts that are correlated with changes in the water table and the snow level. Figure 7, for example, shows a comparison between tilt measurements made near the Grand Canyon of the Yellowstone, the depth of the snow in the region and the height of nearby Lake Yellowstone. The annual cycle is asymmetric, showing a gradual accumulation during the fall and winter followed by a rapid decrease in the spring. The east-west component of the annual cycle is a regional effect; tiltmeters at Madison Junction, Yellowstone and near Lake Yellowstone (about 35 km apart) show the same annual cycle even though the tides at shorter periods are quite different (See Figure 8).

Although our primary interest is in the measurement of long-period effects, we have also used our instruments to investigate more rapid changes in tilt. On 23 February 1982 a hydrofracture test was performed near our tiltmeter site at Erie, Colorado. The hydrofracture was intended to increase the production of a nearby oil well.

The experiment was performed on a 1480-m well which had a 120 mm diameter casing. The bottom 7 m of the casing was perforated. This perforation coincides with the Shafter formation, an oil-bearing relatively low-permeability Cretaceous sandstone.

A sand-laden water-gel was pumped into the well at a constant rate of 4000 l/min. The pumping continued for 84 min, after which the well was sealed. The seal-off pressure was 5.95 x 10^6 N/m^2 (850 psi).

Two of our instruments were located approximately 500 m away. The line from both of the tiltmeters to the well was along an azimuth of 168°. After the tides were removed from the tilt measurements, the residuals were combined to yield the tilt vector component along the axis to the well and perpendicular to that axis. These results are shown in Figures 9.

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### Power Spectral Density

![Graph](image)

**Fig. 6.** The power spectrum of a data set 28 days long. The data were recorded using a pair of horizontal pendulums in a 30-m borehole in Boulder, Colorado. The dotted curve shows the residuals of a fit to remove the diurnal and semidiurnal tides. The long-period and ter-diurnal tides were not removed and the two spectra are therefore identical at these frequencies.
and 10. On both tiltmeters, the components of the tilt along the axis to the well tilted toward the well during the fracture by about 25 nano-radians. The perpendicular components do not show any effect at that time.

This was not a controlled experiment and we do not know the parameters that are needed to estimate the shape or extent of the fracture geometry from our measurements, although the size of the tilt step is consistent with approximate analytic models of the fracture zone. A simple model would suggest that the axis of the fracture should be roughly perpendicular to the axis of maximum tilt or along an azimuth of about 80°, but there is not enough information to construct a quantitative model of the event, and the data are presented primarily to demonstrate the sensitivity of near-surface tilt measurements to relatively small changes in the stress at depth.

Fig. 7. A comparison between tilt measurements made at the Grand Canyon of the Yellowstone and at Lake Yellowstone with the height of the lake and the depth of the snow in the area.

Fig. 8. Comparison of the east-west tilts at Lake Yellowstone and Madison Junction, which is about 35 km west of the lake.

Conclusion

We have constructed a borehole tiltmeter using a pair of small horizontal pendulums. The instrument is capable of resolving tilts with amplitudes of only a few nano-radians. It is totally self-contained, can be installed in 15 cm diameter boreholes, and can operate for long periods of time with little or no maintenance. We have used the instrument in several field investigations in Colorado and Wyoming. These investigations have concentrated on using the earth tides to estimate the elastic parameters of a region and on evaluating the secular performance of the instrument with a view toward measurements that might be useful for earthquake prediction. Additional experiments are currently under way in Southern California near the San Andreas Fault.
Fig. 9. Tilts recorded by two tiltmeters near Erie, Colorado. The tilts measured by the two pendulums in each borehole have been combined to yield the resultant tilt along an azimuth of 168°, which is the azimuth of the line joining the instruments to the well in which the hydrofracture was performed. The x-axis is in days, the y-axis is in nanoradians and the sawtooth curve in the center of the figure is a timing marker.

Fig. 10. The same as Figure 9, except that the data have been used to construct the tilt along an azimuth of 78°, which is perpendicular to the azimuth of the line between the instruments and the well in which the hydrofracture was performed.