Can X–Ray Jets be Cosmic Beacons?

Dan Schwartz, Chandra X–ray Center, SAO

ABSTRACT

The Chandra X-ray Observatory has proven to have unique capability to detect jets and hotspots in quasars and radio sources. If X-rays from *any* of the observed objects are due to inverse Compton scattering of relativistic electrons on the cosmic microwave background (CMB) radiation, then such a source will be detectable with the same surface brightness anywhere in the more distant universe. This is because the enhancement of the CMB energy density by a factor of $(1+z)^4$ compensates for the $(1+z)^{-4}$ decrease of surface brightness. The jets could outshine the parent quasars! Such objects are inferred to exist from present observations, and will therefore serve as Cosmic Beacons. Chandra will soon verify if PKS2215+020 has already been detected as such a beacon.

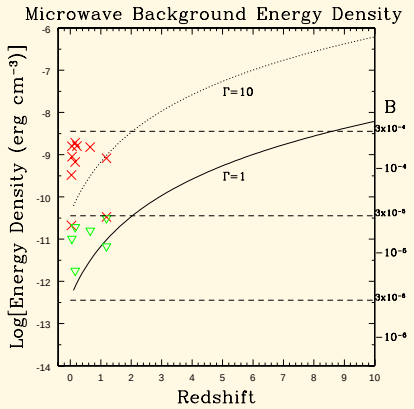

Figure 1. The heavy solid line shows the energy density(left scale) of the CMB as a function of redshift . The right hand scale gives the magnetic field value having the corresponding energy density. Whenever an object at some redshift has a magnetic field less that the CMB line at that redshift, the primary energy loss of electrons is to inverse Compton (IC) scattering on the CMB. The crosses plot equipartition fields in some jets and hotspots from Chandra observations, assuming no bulk relativistic motion. The triangles plot the magnetic field in the source frame for jets, and knots of jets, which are inferred to be in relativistic motion with $\Gamma \sim 5$ to 10. For such motion the CMB energy density is enhanced by Γ^2 in the jet frame, and appears as the dotted curve if $\Gamma = 10$. For these cases the observed X-rays are due to IC/CMB emission. (Data from Harris and Krawczynski 2001, Pesce et al. 2001, Hardcastle et al. 2001, Wilson et al. 2001a,b.)

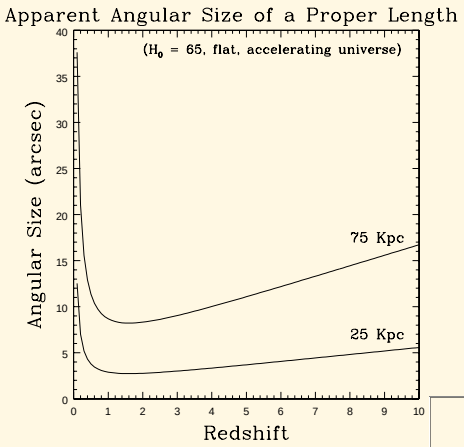

Figure 2. The X-ray jets in PKS 0637-752 (Schwartz et al. 2000), and 3C 273 (Marshall et al. 2001) brighten about 20 to 30 kpc from the quasar core, and extend 50 to 100 kpc (all distances projected in the plane of the sky). We plot the apparent angular size of projected distances of 25 and 75 kpc as a function of redshift. With the 1″ resolution of Chandra, 10 kpc can be resolved anywhere in the universe. Throughout this paper we assume a flat, accelerating cosmology, with H_0=65, $\Omega_0 = 0.3$, and $\Omega_\Lambda = 0.7$, and use the formulas given by Pen (1999).

Introduction

PKS 0637–752the first celestial X-ray target of the Chandra X-ray Observatory, revealed a surprisingly strong X-ray jet coincident with the previously known radio jet (Schwartz et al. 2000). The great difficulty in explaining the X-ray emission *and* allowing the magnetic field and relativistic electrons to be near equipartition, led Tavecchio et al. (2000) and Celotti et al. (2001) to suggest that the extended jet structure was in bulk relativistic motion with $\Gamma \sim 10$ on scales greater than 100 kpc. While this may be controversial if suggested as a common property of quasar jets, it would explain the one-sidedness of arcsec scale jets. Furthermore, that quasars do have pc scale jets relativistically beamed toward us is well supported by observations of superluminal motion, and is fundamental to the various unified theories of AGN taxonomy. With Chandra detection of X-ray jets soon to be in the tens of objects, models for at least 3C 273 (Sambruna et al. 2001), and 3C 371 (Pesce et al. 2001) also call for large scale beaming.

We point out here that if relativistic beaming is common, we should see X-ray jets from those sources pointed toward us *anywhere in the universe*. Even powerful unbeamed sources may be seen at all redshifts, if their intrinsic magnetic fields are somewhat less than the typical values $\sim 2\times10^{-4}$. This follows from the standard relation that the ratio of IC power to synchrotron power is the ratio of the energy density of target photons to the magnetic field energy density (Felten and Morrison 1966). The CMB energy density increases with redshift according to $(1+z)^4$. Fig. 1 shows energy densities vs. redshift. This factor compensates for the decrease of surface brightness due to the expanding universe. X-ray jets are resolved by Chandra and will always be resolved (on-axis) anywhere in the universe (Fig 2.).

As the jets maintain their apparent surface brightness, they can even outshine the quasar cores, (see Fig 3.). Such a case might be speculated for PKS 2215+020 (Fig. 4), at z=3.572, where ROSAT detects an unusually high X-ray to optical flux ratio, (Siebert and Brinkmann 1998). The IC X-rays arise from lower energy electrons than those emitting at GHz frequencies, and their lifetimes will be long enough to propagate to 100 kpc scales, Fig 5. For extremely luminous quasars, photons from the core might contribute to the IC target density at low redshifts, Fig 6.

Fig. 7 simulates the appearance of a jet in an actual 132Ksec Chandra deep field (Giacconi et al. 2001). We took an observed image of the PKS0637-752jet, modelled according to Tavecchio et al., (2000), reduced its luminosity at the actual z=0.652 by a factor of 27, and then scaled to the IC flux which would be observed at z=4. While only marginally visible to the eye in the raw level 1 image, there are 112 counts above the background level of 45.

Simulated Jet at z=4

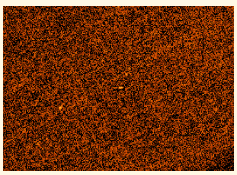

Figure 7. Simulated image of a jet which is a factor of 27 times less luminous than PKS 0637-752, detected at a redshift z=4 in an exposure of 132 Ksec. Created by superposing a 4855 image of just the jet of PKS 0637 onto one of the CDF south observations. The jet can be seen near the center, even in this unfiltered Level 1 event image. The quasar core would now be three times weaker than the jet, and is not included in the simulation.

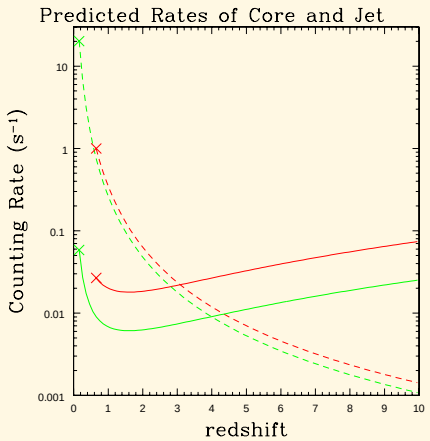

Figure 3. Predicted counting rates of the cores, (dashed lines), and jets, (solid lines), of PKS 0637-752 (in red) and 3C 273 (in green), if they were at larger redshifts. The predictions are scaled from the Chandra observations, shown as crosses at the redshift of each object. At redshifts beyond a few the jet emission dominates, and it might be that only the jet is detectable.

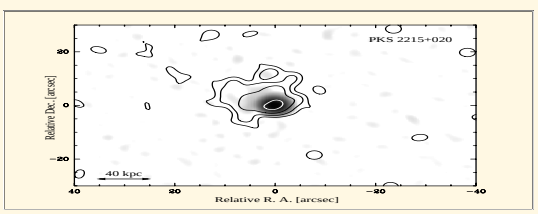

Figure 4. ROSAT HRI contours of the quasar PKS 2215+020, overlaid on a VLA 5GHz image (gray scale). Taken from Lobanov et al., (2001). The VLA extension is along the direction of a complex, milliarcsec jet discussed in Lobanov et al. This is one of the highest redshift jets known, with z=3.572, and a good candidate for an IC/CMB X-ray jet. Siebert and Brinkmann (1998) caution that the ROSAT contours are not inconsistent with the point spread function, and that the 4.″5 position offset is also consistent with the boresight errors. Nonetheless, the extreme $\alpha_{ox} \sim 0.8$ for this object could indicate a strong, non-nuclear X-ray component. We will observe this object in the Chandra AO-3 cycle, and expect to resolve a jet stronger than 1 percent of the quasar core.

Conclusions

We should vigorously search for distant X-ray jets in both wide field and deep field surveys.

- **Observational Implications**
  - Jets may be displaced by 5″ to 10″ from the optical object which emits them. They may therefore be blank fields within the location capability of ROSAT, Chandra, and XMM/Newton. They might also be incorrect identifications of chance coincidences with optical objects.
  - Jets require $\leq 1''$ angular resolution for clear identification. If resolved, the jet should point toward the AGN.
  - Algorithms to detect extended sources for telescopes with poorer resolution, e.g. when more than 5′ offaxis in Chandra, must fit to a linear shape, *not* to a circularly symmetric shape.
- **What Can We Learn?**
  - **Cosmogony and Jet Physics**
    - Discover distant, early activity in the universe.
    - Verify the common occurrence of relativistic beaming on 100 kpc scales. If this occurs, X-ray jets are certain to be seen at any redshift at which they exist.
    - Is the CMB the limiting dynamical factor in radio lobe and jet formation?
    - Are jets established before the accretion luminosity in the core becomes significant? (Case of no optical counterpart to a jet.)
    - Are there radio quiet X-ray jets? Could happen if 'radio' electrons at higher γ have lost their energy to gamma rays, or if larger jet structures can transport upwards of 10^{48} erg s^{-1} while $B \leq 10^{-7}$ Gauss.
    - Do jets produce an appreciable component of the X-ray background? This may be just a curiosity, as the background clearly arises from quasars in any case.
  - **Cosmology**
    - Measure the temperature of the cosmic microwave background *in situ*.
    - Verify the decrease of surface brightness according to $(1+z)^{-4}$ (Tolman effect; Sandage 1961; Sandage and Lubin 2001)

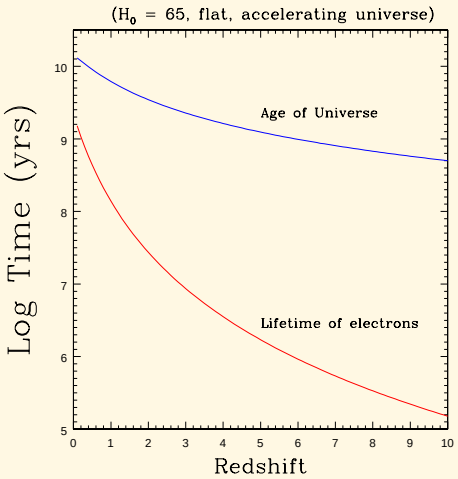

Figure 5. In the absence of bulk relativistic motion, electrons with $\gamma \sim 1000$ will scatter off the microwave background photons at any redshift to give X-rays observed at $\sim$1 keV. The lifetime of such electrons as a function of redshift is given in the lower, heavy curve. The lifetimes are long enough to propagate from the nucleus out to 100 kpc scales, but less than the 10^8 years typically deduced for radio sources. Thus the CMB may play a significant role in the dynamics of radio source formation in the early universe. Alternately, the large kinetic power inferred for jets might replenish the electron losses.

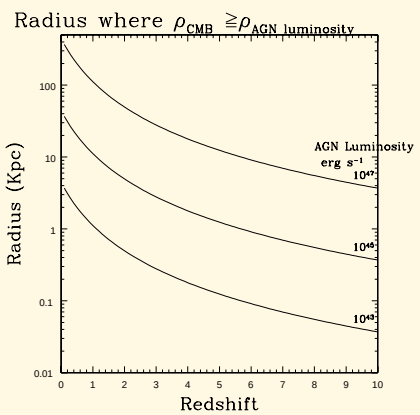

Figure 6. The CMB energy density will dominate over the energy density due to the luminosity of the core, at larger redshifts or larger distances than traced out by the solid lines given for three fiducial core luminosities. The core is assumed to radiate isotropically.