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On the origin of radio emission in radio quiet quasars

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Abstract. The radio emission in radio loud quasars (RLQs) originates in a jet carrying relativistic electrons. In radio quiet quasars (RQQs) the radio emission is $\sim 10^3$ times weaker, relative to other bands. Its origin is not clearly established yet, but it is often speculated to arise from a weak jet. Here we show that there is a tight relation between L_R and L_X for RQQs, with $L_R/L_X \sim 10^{-5}$, based on the optically selected Palomar-Green (PG) quasars, with nearly complete X-ray and radio detections (avoiding biases and selection effects). Coronally active stars also show a tight relation between L_R and L_X with $L_R/L_X \sim 10^{-5}$ (the Güdel & Benz relation), which together with correlated variability indicates that stellar coronae are magnetically heated. The X-ray emission of quasars most likely originates from a hot accretion disk corona, and since RQQs follow the Güdel & Benz relation, it is natural to associate their radio emission with coronal emission as well. The tight relation between L_R and L_X may simply reflect the equality of accretion disk coronal heating by magnetically generated relativistic electrons (producing L_R), and coronal cooling by Compton scattering (producing L_X). This suggestion can be tested by looking for correlated X-ray and radio variability patterns, such as the Neupert effect, displayed by stellar coronae.

Key words. Galaxies: active – quasars: general – Radio continuum: galaxies – X-rays: galaxies

1. Introduction

The overall spectral energy distribution (SED) of quasars has a characteristic shape, with a relatively small dispersion (e.g. Sanders et al. 1989), except in the radio band, where there is evidence that the distribution of relative radio power, commonly measured using $R \equiv f_{6\ \mathrm{cm}}/f_{4400\ \mathrm{Å}}$, is bimodal, with RLQs having $R \sim 10^2 - 10^5$ and RQQs having $R < 0.1 - 10$ (Kellerman et al. 1989). The radio emission of RLQs originates in a relativistic jet, as clearly established through high resolution radio imaging (Blandford & Rees 1974), however the origin of the radio emission in RQQs is not established yet.

Early radio imaging of RQQs confined the radio emission to arcsec scale, which allowed the option of starburst related radio emission. As the sensitivity of radio telescopes increased, higher resolution imaging of RQQs became available, limiting the radio emission to a mas or pc scale. Most recently, radio variability of RQQs confine the radio emission to < 0.1 pc, which clearly indicates a compact non thermal source (Barvainis et al. 2005). Unlike high resolution imaging of RLQs, which often resolves a significant fraction of the total radio flux al-

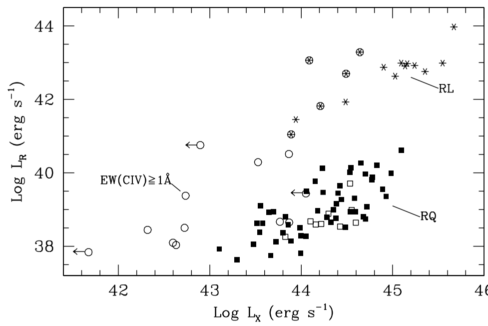

Fig. 1. The distribution of the PG quasars in the $L_{\rm R}$ vs. $L_{\rm X}$ plane. RLQs are designated by stars, and their $L_{\rm R}/L_{\rm X}$ is on average a factor of 10^3 higher than for RQQs. Circles mark objects with C IV absorption EW$>$ 1Å (some of which are RL), where left attached arrows mark upper limits to $L_{\rm X}$. These UV absorbed AGN tend to be underluminous by a factor of 10-30 in $L_{\rm X}$ for a given $L_{\rm R}$ due to absorption. Squares are RQQs without C IV absorption, where the filled/empty squares mark objects with radio detections/upper limits. Note the small scatter in the $L_{\rm R}$ vs. $L_{\rm X}$ correlation in RQQs, once RLQs and UV absorbed quasars are excluded.

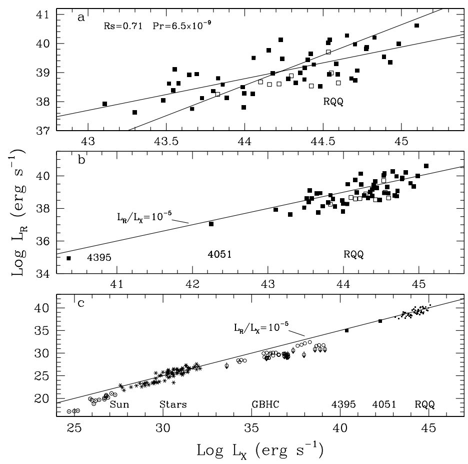

Fig. 2. Panel a, same as in Fig.1, including only the RQQs without UV absorption. The Spearman rank order correlation strength and its significance is indicated in the upper left corner. The two lines mark least square fits minimizing the deviations in either $L_{\rm R}$ or $L_{\rm X}$. Panel b, zoom out to include the two lowest luminosity type 1 AGN, which are well studied in the X-rays. Most objects are within a factor of few from the solid line which marks $L_{\rm R}/L_{\rm X} = 10^{-5}$ (it is not a fit). Panel c, further zoom out to include GBHC, coronally active stars, and individual solar flares. Coronally active stars also lie close to $L_{\rm R}/L_{\rm X} = 10^{-5}$, which raises the possibility that both $L_{\rm R}$ and $L_{\rm X}$ in RQQs originate in coronal emission.

ready on an arcsec scale, in RQQs the emission remains largely unresolved down to mas scale. *What produces this radio emission?* A plausible explanation is a scaled down version of the RLQ mechanism, i.e. a weak jet which dissipates already on sub pc scale. However, the bimodal distribution in jet powers would remain unexplained. Below we show that the radio emission in RQQs is strongly correlated with the X-ray emission, a correlation which may point at the origin of the radio emission in RQQs.

2. The Radio - X-ray correlation

A significant Radio - X-ray (R-X) correlation was found in earlier studies of quasars (e.g. Brinkmann et al. 2000). However, these studies were based on incomplete samples, selected in the X-ray or radio regimes, which can lead to spurious correlations (e.g. if both luminosities are correlated with z). To avoid these biases we study the R/X correlation using the $z < 0.5$ subsample of the optically selected PG quasar sample (Boroson & Green 1992), selected independently of the X-ray and radio emission properties, which was studied extensively over a wide range of energies. Radio and X-ray fluxes are available for $\sim$ 90% (78/87) and $\sim$ 97% (84/87) of the objects. Figure 1 presents the distribution in the $L_{\rm R}$ vs. $L_{\rm X}$ plane. Excluding the 16 RLQs in this sample (as we are interested in RQQs), and the 17 objects having C IV line absorption equivalent width $>$ 1 Å (as such objects are X-ray absorbed). This leaves a sample of 59 unabsorbed RQQs. The small dispersion in the R-X correlation is remarkable, in particular since the X-ray emission is known to be significantly variable, and the radio observations were taken about 10 years before the X-ray observations (early 80s vs. early 90s). This suggests that the intrinsic scatter in the R-X relation is smaller than measured here.

How far down in luminosity does the R-X relation extends? Unfortunately, there is no optically selected sample of low luminosity type 1 AGN with nearly complete X-ray, UV, and radio detections, as the PG sample used above. However, in Figure 2b we show the two best studied lowest luminosity type 1 AGN, NGC 4395 and NGC 4051, which suggest that the R-X correlation may extend a factor of $\sim 10^3$ further down in luminosity from $L_X \sim 10^{43}$ erg s^{-1} to 10^{40} erg s^{-1}.

3. Implications

The X-ray emission in RQQs is clearly not strongly beamed, thus the R-X correlation indicates that the radio emission in RQQs is also not strongly beamed. If the radio originates in a jet, the jet should be non relativistic. Furthermore, the jet power should be correlated with the coronal disk emission, which generates the X-ray power-law emission in AGN (e.g. Falcke et al. 2004). However, there may be a more direct R-X relation, as indicated by the Güdel-Benz relation in coronally active stars.

In Figure 2c we plot a compilation of radio and X-ray luminosities of various types of coronally active stars from Benz & Güdel (1994). Quite remarkably, both coronally active stars and active galaxies appear to follow the same R-X relation, despite the $\sim$ 15 orders of magnitude in luminosity between these two types of active objects. The X-ray emission in RQQs is commonly interpreted as originating in hot coronal gas, although unlike stellar coronae, in AGN the coronal X-ray cooling is mostly generated through comptonization of the softer photospheric disk photons, rather than through pure thermal emission. AGN coronae are also commonly thought to be magnetically dominated, and possibly magnetically heated, although there is still no direct evidence for that. The similarity of the R-X relation in active stars and active galaxies, and the potential similarity in their X-ray emission source, naturally raises the possibility for a similar radio emission mechanism. Namely, that the radio emission of RQ AGN originates in a magnetically active corona above the accretion disk, rather than in a weak jet.

How can this interpretation be tested? Coronally active stars sometimes show correlated X-ray and radio variability. In particular, the so-called Neupert effect, where a radio flare is followed by an X-ray flare, with the relation $dL_X/dt \propto L_R$ (Güdel 2002). This variability pattern is interpreted as a magnetic reconnection event in the corona, which accelerates electrons, producing a synchrotron emission spike. The high energy electron beam dumps its energy collisionally in the cooler chromospheric gas, heating it to coronal temperatures, and thus raising the coronal X-ray emission. If the X-ray cooling time is much longer than the radio cooling time, then the X-ray emitting gas serves as a bolometer for the time integrated heating, while the radio emission is proportional to the instantaneous heating rate, explaining the Neupert effect. Simultaneous Radio and X-ray monitoring of RQQs may thus provide further evidence for the coronal origin of the radio emission in RQQs, and may thus shed some light on the coronal heating process in AGN.

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