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The High-Frequency Flares in Markarian 231

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We report on high-frequency (22 and 43 GHz) EVLA and VLBA monitoring of the nearby broad absorption line quasar, Mrk 231. These observations have shown that, in spite of its classification as a radio quiet quasar, Mrk 231 has a highly dynamic radio core and exhibits large flares at high frequency. Further, we find evidence that the relativistic plasma is ejected along a trajectory close to the line of sight and is significantly Doppler boosted. Our monitoring campaign aims to elucidate why such strong flares cool off and never link to large scale radio lobes and we present preliminary models of the source environment that are consistent with our observations.

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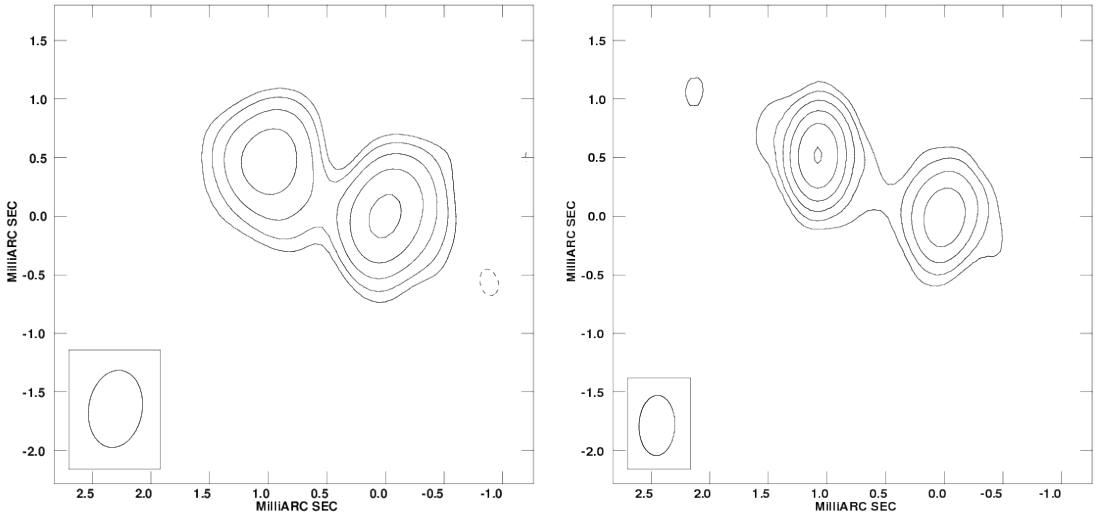

Figure 1: VLBA 22 GHz images of Mrk 231 from epochs 2006.06 and 2006.32. The contours start at 1.8 mJy/beam and increase in factors of 2 to a maximum of 57.6 mJy/beam.

1. Introduction

Mrk 231 is a nearby ($z = 0.042$) radio quiet quasar which displays a remarkable range of phenomona associated with its active galactic nucleus (AGN). These phenomena include broad absorption lines, broad emission lines, a very high thermal luminosity ($L_{bol} \sim 2 \times 10^{46}$ erg s^{-1} from the central engine) and a radio jet. Optically, Mrk 231 is normally classified as a Seyfert I, and in addition to its AGN, the host galaxy has a strong starburst contribution. Its optical morphology strongly suggests that it has undergone a recent merger. The rich features of this particular QSO were recognised early on, inspiring [1] to title a paper on the source “The remarkable Seyfert galaxy Mrk 231".

The presence of the radio jet, and the proximity of the source to Earth, make Mrk 231 ideal for studying the high kinetic luminosity relativistic ejecta in radio quiet quasars. The 22 – 43 GHz flux density of Mrk 231 is approximately 80 mJy in its quiescent state, and most of this flux density resides in a compact core and compact secondary displaced by only 1 mas, thus making it a viable target for the VLBA at high frequency. When observed at high frequency (22 – 43 GHz) this source is observed to undergo large, rapidly evolving flares which form the subject of this article.

2. The High-Frequency Flare in 2006

At 22 GHz the VLBI continuum source in Mrk 231 comprises a compact double source (see Figures 1 and 2). The northeast component is the radio core (as evidenced by its relatively flat spectrum and short timescale variability), the southeast secondary component appears to be a compact radio lobe, with a steep spectrum ($\alpha = 2.2^*$ between 22 and 43 GHz) resulting from free-free absorption in the surrounding gas [11].

$^*S_\nu = \nu^{-\alpha}$

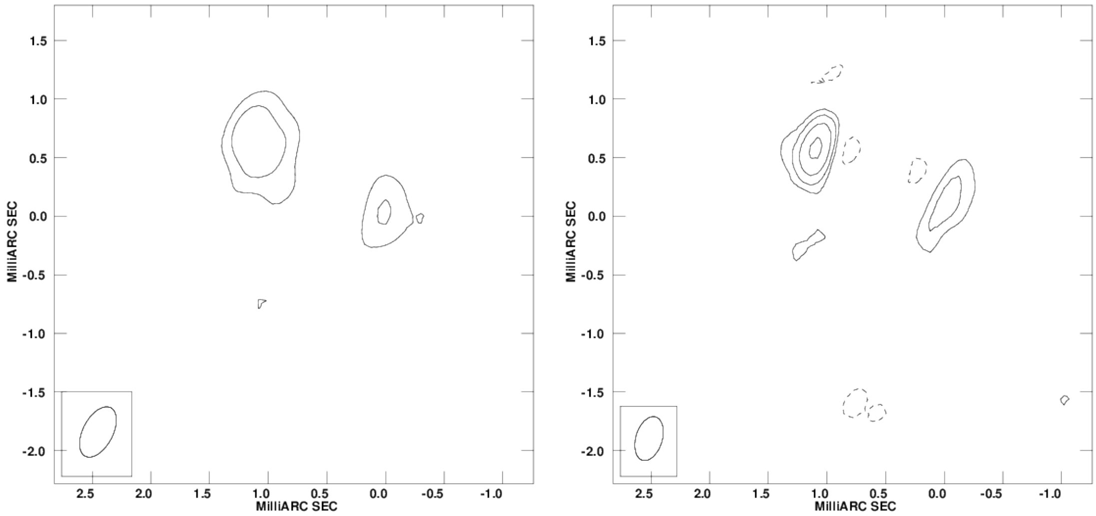

Figure 2: VLBA 43 GHz images of Mrk 231 from epochs 2006.06 and 2006.32. The contours start at 2.2 mJy/beam and increase in factors of 2 to a maximum of 17.6 mJy/beam.

We carried out 2 epochs of VLBI observations in January and April of 2006 using all ten antennas of the VLBA at frequencies of 8, 15, 22 and 43 GHz. The observations were phase referenced to a nearby ICRF calibrator (J1302+5748) to facilitate detection of the relatively weak target source and provide some astrometric information.

The 22 and 43 GHz images are presented in figures 1 and 2. The morphology of the source is almost unchanged between the two epochs, but the flux density in the core changes dramatically. Figure 3 shows the spectrum of the source between 15 and 43 GHz at the two epochs and also includes spectra from the literature ([11] and [12]) and VLBA archive. The secondary component shows no significant change in flux density at any frequency, in keeping with previous measurements since 1996 ([11] and archival VLBA images). The core component however shows a large increase at 15 and 22 GHz, indicative of a rapidly evolving flare. The 43 GHz flux density is not very different between the two epochs indicating that the flare has already run its course at this higher frequency, while it is still in progress at 15 and 22 GHz. An in-depth analysis of this flare and its implications for the nuclear environment is given in [9], the highlights of which are presented here.

The most striking feature of the flare is the change in spectrum between 2006.07 and 2006.32. The steep spectrum between 15 and 43 GHz changes to an inverted spectrum between 15 and 22 GHz and a very steep spectrum between 22 and 43 GHz. This unusual spectral change in just 91 days provides strong constraints on the nature of the flare, and the strong cooling mechanism at play.

The possibility of a free-free absorbing screen causing the inverted spectrum between 15 and 22 GHz is discounted by consideration of the spectral luminosity (L_ν) in such a scenario. Following [13], the spectral luminosity for a power-law synchrotron spectrum seen through a free-free absorbing gas is:

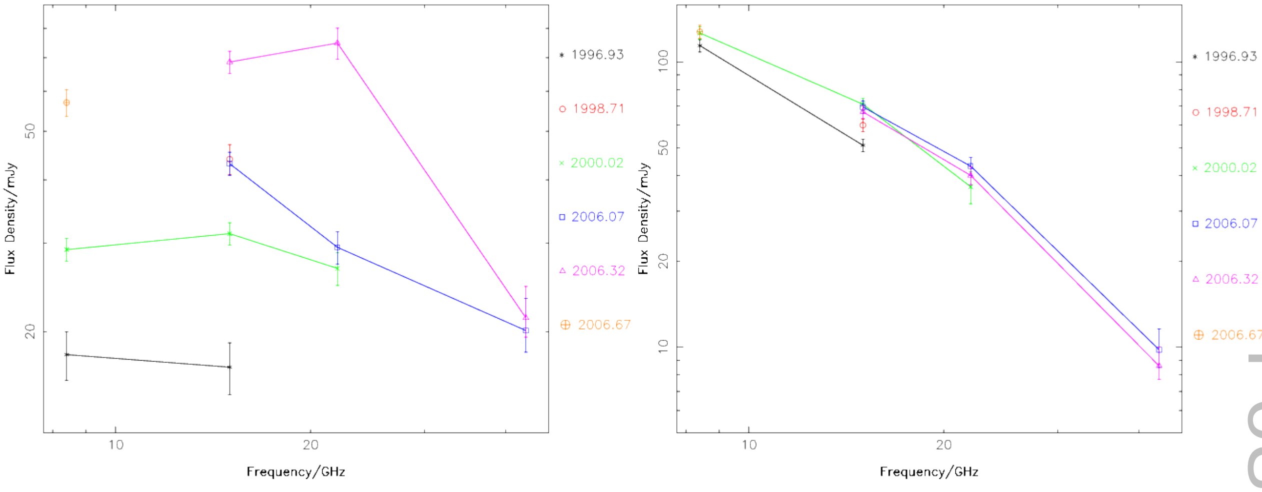

Figure 3: The spectra of the core and secondary components in Mrk 231 from our observations and all available VLBA archival data (including [11], [12]).

$$L_\nu = L_0 \times \left(\frac{\nu}{2.2\times10^{10}\mathrm{Hz}}\right)^{\alpha}[(1-f)+fe^{-\kappa(\nu)}] \tag{2.1}$$

$$\kappa(\nu) = 9.8\times10^{-3}L_{\mathrm{pc}}N_e^2T^{-1.5}\nu^{-2}[17.7+\ln(T^{1.5}\nu^{-1})]\,. \tag{2.2}$$

where N_e is the number density of free electrons, T is the temperature, f is the filling factor of the screen, and L_{pc} is the thickness in parsecs. Fitting for the flux density at our 3 frequencies of measurement over a range of temperatures ($10^3 < T < 5\times10^5$ K) using reasonable assumptions for the source geometry and the filling factor of the free-free absorbing screen we find that the background synchrotron source has an intrinsic spectral index $\alpha \sim 3.1$ which must be considered unrealistic.

An alternative model for the spectral luminosity is to consider radiative transfer through a synchrotron self absorbed (SSA) plasma. We perform the calculation in the plasma rest frame using known variables from observation. Following [3] and [8] we have the following parametric form for L_ν from the SSA source, where the observed quantities are designated with a subscript, “o":

$$L_\nu = \frac{L_0\nu^{-\alpha}}{\mu(\nu)} \times \left(1-e^{-\mu(\nu)R}\right)\,, \tag{2.3}$$

$$\mu(\nu) = \frac{3^{\alpha+1}\pi^{0.5}g(p)e^2N_\Gamma}{8m_ec}\left(\frac{eB}{m_ec}\right)^{(1.5+\alpha)}\nu_o^{(-2.5+\alpha)}\delta^{(2.5+\alpha)}\,, \tag{2.4}$$

$$g(n) = \frac{\Gamma[(3n+22)/12]\Gamma[(3n+2)/12]\Gamma[(n+6)/4]}{\Gamma[(n+8)/4]}\,, \tag{2.5}$$

where $\nu = \nu_o/\delta$, and R is the radius of the spherical region in the rest frame of the plasma. The Doppler factor, δ, is given in terms of Γ, the Lorentz factor of the outflow; β, the three velocity of the outflow and the angle of propagation to the line of sight, θ; $\delta = 1/[\Gamma(1-\beta\cos\theta)]$ [6].

If we assume that the source is spherical and homogeneous, then we have three variables in equation 2.3 (μ_o, α and L_o) and we have three equations (the 3 measured flux densities converted

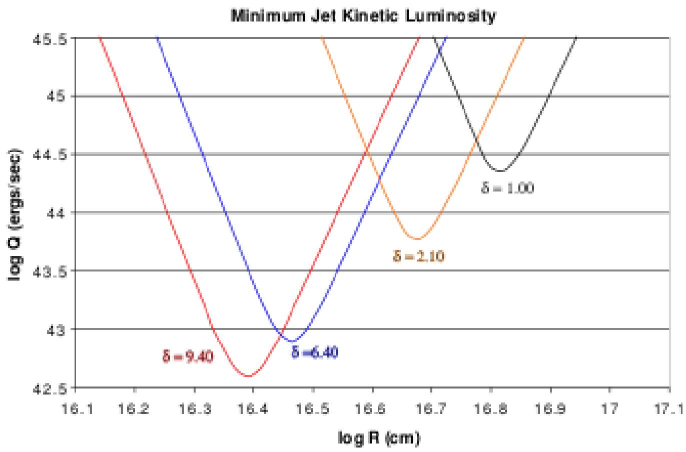

Figure 4: The minimum kinetic energy flux, Q, for homogeneous spherical source models as a function of R and Doppler factor, δ.

into spectral luminosities in equation 2.3). Thus we can fit the three flux density measurements to find $\alpha = 2.26$. Although this is very steep for a radio source it is still much more reasonable than the free-free absorption solution. Thus, SSA is a much more likely explanation of the peak in the synchrotron spectrum than free-free absorption.

The synchrotron emissivity is given in [10] as

$$j_\nu = 1.7 \times 10^{-21} (4\pi N_\Gamma) a(n) B^{(1+\alpha)} (4 \times 10^6/\nu)^\alpha \,, \tag{2.6}$$

$$a(n) = \frac{\left(2^{\frac{n-1}{2}}\sqrt{3}\right)\Gamma\left(\frac{3n-1}{12}\right)\Gamma\left(\frac{3n+19}{12}\right)\Gamma\left(\frac{n+5}{4}\right)}{8\sqrt{\pi}(n+1)\Gamma\left(\frac{n+7}{4}\right)} \,, a(5.52) = 0.102 \,. \tag{2.7}$$

We can relate this to the observed flux density, $S(\nu_o)$, in the optically thin region of the spectrum (43 GHz) using the relativistic transformation relations from [6],

$$S(\nu_o) = \frac{\delta^{(3+\alpha)}}{4\pi D_L^2} \int j'_\nu dV' \,, \tag{2.8}$$

where D_L is the luminosity distance and j'_ν is evaluated in the plasma rest frame at the observed frequency. A second equation arises from our SSA fit to the data above,

$$\mu(\nu = 19.5\mathrm{GHz})R = 1 \,. \tag{2.9}$$

Since we already determined $\alpha = 2.26$ then the pair of equations 2.8 and 2.9 with the expansions of equations 2.3 and 2.7 indicate that we have two equations in four unknowns, R, B, δ and N_Γ.

We explore solutions of these equations for a range of Doppler factors: $\delta = 1.00$ (non-relativistic), $\delta = 2.10$ (mildly relativistic), $\delta = 6.40$ and $\delta = 9.40$ (highly relativistic). We plot the resulting $Q_{min}(R)$ values in Figure 4 for each of the four values of δ. Each of the four plots of $Q_{min}(R)$ has a minimum that we designate as the minimum kinetic energy flux for that value of δ, Q_{min}.

The ratio of inverse Compton luminosity, L_{ic}, to synchrotron Luminosity, L_{synch} was calculated in [7] as

$$\frac{L_{ic}}{L_{synch}} = \left(\frac{T_b G(\alpha,z)^{1/5}}{10^{12.22}}\right)^5 \left[1+\left(\frac{T_b G(\alpha\,,\,z)^{1/5}}{10^{12.22}}\right)^5\right] , \tag{2.10}$$

$$G(\alpha\,,\,z) = \left[\frac{\nu_{\rm op}/\delta}{3.5\,{\rm GHz}} + \frac{\nu_{\rm op}/\delta}{(1+z)1\,{\rm GHz}} \times \left[\left(\frac{\nu_{\rm high}}{(1+z)\nu_{\rm op}}\right)^{(1+\alpha)} - 1\right]\right] f_3(\alpha)^{-4}(1+z)^4 \tag{2.11}$$

where $\nu_{\rm op} = 19.5$ GHz is the peak in the observed SSA spectrum, $\nu_{\rm high} = 43$ GHz is the highest frequency in the power law in the observer's frame.

For the minimum kinetic energy flux solution with $\delta = 1$ equations 2.10 and 2.11 imply that $L_{ic}/L_{synch} \approx 2\times10^8$. The X-ray observations from 0.2 – 50 keV from [2] indicate a total intrinsic X-ray luminosity of $L_X \sim 10^{44}$ergs/s. Combining this with our measured radio luminosity of the core we find that

$$\frac{L_{ic}}{L_{synch}} \sim \frac{10^{44}{\rm ergs/s}}{10^{41}{\rm ergs/s}} = 10^3 \, . \tag{2.12}$$

Thus, the $\delta = 1$ minimum kinetic energy flux solution is inconsistent with the value of L_{ic}/L_{synch} determined by observation. Further, the $\delta = 1$ solution gives $T_b/T_{max} \sim 0.86$ (where T_{max} is the inverse Compton limit). A source with T_b so close to the Compton limit would be expected to be a bright X-ray source and to have diminished radio luminosity [4]. The intrinsic X-ray luminosity is $L_X \approx 1\times10^{44}$ergs/s [2] which is at the low end of the intrinsic X-ray luminosity distribution for a quasar with the thermal luminosity of Mrk 231 ($L_{bol} \gtrsim \times 10^{46}$ergs/s [5]). Thus, the strong intrinsic radio emission and the relatively weak intrinsic X-ray emission (by radio quiet quasar standards) are not consistent with T_b near the Compton limit.

To make the $\delta = 1$ solution consistent with the observed value of L_{ic}/L_{synch}, one could consider larger values of R which would give lower model values of T_b. However, from Figure 4, the values of R which achieve this imply $Q \sim 10^{46}$ ergs/s, the power of the strongest known FR II radio jets [14]. This seems unlikely for a radio quiet quasar.

On the other hand, the $\delta = 9.40$ solution at $R = 3.12\times10^{16}$ cm gives an intrinsic value of $T_b^{'} = T_b/\delta = 3.7\times10^{11}$ K [7] implying that $L_{ic}/L_{synch} \lesssim 10^3$ and $Q \sim 3.5\times10^{43}$ ergs/s. This value of Q seems like a more reasonable value for an outburst in a radio quiet quasar, being similar to the average Q in a strong FR I radio galaxy [14].

It therefore seems likely that the subparsec scale radio jet in Mrk 231 is highly Doppler boosted, i.e. relativistic and viewed approximately pole-on.

3. How Frequent are the High-Frequency Flares in Mrk 231?

Figure 5 gives the historical integrated flux density of Mrk 231 at 22 GHz. The quiescent flux density is approximately 100–120 mJy and from the historical light curve we can see that the integrated flux density significantly exceeds the quiescent value about half the time. Although in general we do not know very much about the phenomena that led to those historical periods of enhanced 22 GHz emission, we estimate that the source probably flares at least once per year.

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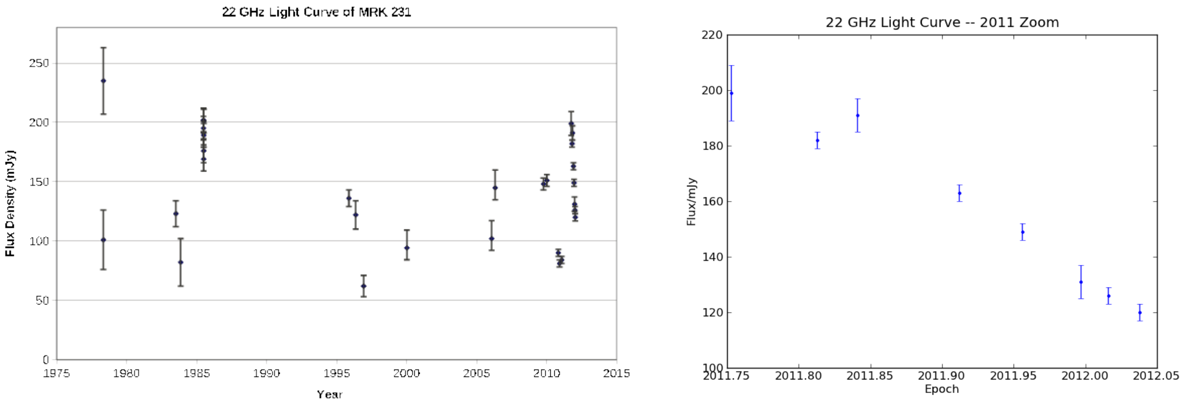

Figure 5: The 22 GHz lightcurve formed from all known 22 GHz observations of Mrk 231 in the literature, the VLA archive and from our own VLA monitoring. The left panel shows the historical lightcurve of all known 22 GHz measurements. The right panel is a zoom in of our most recent EVLA monitoring campaign, showing clear evidence for a very rapidly decaying flare, similar to that which prompted the monitoring campaign [9].

This makes it an ideal candidate for a monitoring campaign, which would attempt to identify the early onset of a flare and then follow it up with high resolution (VLBI) observations in order to determine the nature of the rapidly evolving flares with greater precision than was possible with our previous serendipitous VLBI observations of the 2006 flare. We began such a monitoring campaign in 2009, and have so far been unfortunate to narrowly miss the onset of two more flares due to gaps in our EVLA monitoring campaign. In particular, the right hand panel of Figure 5 shows clear evidence for a very rapidly decaying flare, whose 22 GHz properties are very similar to that of the original flare described in [9] that led to the initiation of this monitoring campaign. Unfortunately a gap in our EVLA observing campaign led us to miss the onset of that flare. The 22 GHz flare was already very evolved and in the fading stage and so the VLBA follow up observations were not invoked.

In order to guarantee a continuous time series and avoid missing future flares, we are now monitoring Mrk 231 with the AMI (Arcsecond Microkelvin Imager) telescope which provides a more efficient means of carrying out the monitoring at a highest frequency of 18 GHz.

4. Conclusions

We have used high frequency (22 and 43 GHz) VLBA observations to determine that the jet in the nearby broad absorption line QSO Mrk 231 has a significant Doppler factor indicating relativistic motion close to the line of sight.

The most striking finding was the strong 22 GHz flare that emerged from the core between epochs 2006.07 and 2006.32. The core spectrum, during the flare, transitions from being very steep spectrum, $\alpha \approx 2$, above 22 GHz to being inverted between 15 and 22 GHz. The magnitude of the flare combined with the three month interval between observations sets a lower bound on the time variability brightness temperature of $T_b > 2 \times 10^{10}$ K, below the inverse Compton limit ($\sim 10^{12}$ K). However, all attempts to model the high frequency peak of the spectral turnover, 19.5

GHz, in combination with the steep spectral index above 22 GHz ($\alpha \approx 2$) indicate that the flare is synchrotron self-absorbed and $T_b \approx 10^{12}$ K, unless the flux density is Doppler boosted. Our Doppler boosted models indicate a kinetic energy flux, $Q \sim 3 \times 10^{43}$ergs/sec and an intrinsic (rest frame of the plasma) brightness temperature $\gtrsim 10^{11}$ K.

These flares appear to be relatively frequent in this source (occurring at least once per year), and as a result we have embarked on a monitoring campaign, originally with the EVLA and now with AMI. The purpose of this monitoring campaign is to identify the early onset of a flare which will then be followed up with multi-epoch high frequency VLBA observations to provide more complete information on the flare growth and decay time scales. This would then further constrain our model of the source. In particular, such observations should reveal how these powerful flares cool off so fast that Mrk 231 never becomes a strong FR I radio source and what are the details of the powerful cooling mechanism.

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