The millimeter variability of M81*

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Abstract. M81*, the nucleus of the nearby spiral galaxy M81 (NGC 3031) is an LLAGN with a luminosity < $10^{-5}$ times the Eddington luminosity of the related supermassive black hole. It appears to have very similar characteristics to Sagittarius A (Sgr A*), the radiative counterpart of the black hole at the center of the Milky Way. Here, we present simultaneous observations at 3 and 1 mm that were obtained within the framework of a coordinated, multi-wavelength campaign on M81*. We find that at mm-wavelengths M81* is a continuously variable source with the higher variability observed at the shorter wavelength. The variability at 3 and 1 mm appears to be correlated. The data show that M81* is indeed a system with very similar physical properties to Sgr A*. The observed variability time scales point to an upper size limit of the emitting region of the order 25 Schwarzschild radii. The obtained data clearly demonstrate the usefulness and, above all, necessity of simultaneous multi-wavelength observations of LLAGN.

1. Introduction

Until about a decade ago, models of accretion onto black holes (BHs) and the related emission were largely concentrated on thermal emission from thin disks. However, the vast majority of galactic nuclei (at least in the local universe) radiate many orders of magnitude below the Eddington limit. These systems have become observable only since high-resolution, high-sensitivity instrumentation has become available in the (sub)mm, the infrared, and the X-ray domains.

Sub-Eddington accretion flows onto BHs in Low Luminosity AGN, LINERs, and almost quiescent nuclei are clearly distinguished from classical AGN by the absence of the so-called “blue bump” in the optical/UV, that is attributed to thermal emission from an optically thick, geometrically thin accretion disk [17]. In highly sub-Eddington systems (in the following called simply “LLAGN”, for brevity), on the other hand, accretion is modeled by radiatively inefficient accretion flows (RIAFs), such as the ADAF [24, 25, 30, 31]. Combined RIAF+outflow models are highly successful in describing the SED of LLAGN, in fact, jets appear to become increasingly important with decreasing overall luminosity of the sources [12, 29, 16]. LLAGN appear to be up-scaled versions of the low/hard state (LHS) of X-ray binaries, which is characterized by the presence of fairly constant, mildly relativistic jets. A universal correlation between X-ray and radio luminosity appears to hold across a range of $> 10^7$ in BH mass [16, 5, 14, 22, 13]. However, the regime of high masses and low Eddington luminosities is still poorly explored and needs to be investigated in order to close the gap in the claimed scaling relation. It seems that synchrotron and SSC/IC from a region very close to the BH is responsible for the submm to X-ray regime in LLAGN. Whether this region is the inner parts (likely outflowing winds) of an RIAF or the base of a jet, or the interface region including both, is still under debate.
Table 1. Observations of M81* with the PdBI during February and July 2005. Start and stop times in UTC. ν₃ is the exact frequency used around 3 mm, ν₁ the one at a wavelength of 1 mm. The last four columns list the ranges of the rms values of the phase, Φ, and amplitude, A, between all baselines for each observing epoch and wavelength (σΦ,3 and σA,3 for 3 mm and σΦ,1 and σA,1 for 1 mm).

| Start          | Stop            | ν₃ [GHz] | ν₁ [GHz] | σΦ,3 [deg] | σA,3 [%] | σΦ,1 [deg] | σA,1 [%] |
|----------------|-----------------|---------|----------|------------|----------|------------|----------|
| 24-02 01:11    | 24-02 19:45     | 115.3   | 230.5    | 10-20      | 5-8      | 20-40      | 11-18    |
| 14-07 06:50    | 15-07 13:51     | 80.5    | 241.4    | 15-35      | 8-11     | 40-60      | 25-30    |
| 19-07 23:17    | 20-07 16:07     | 86.2    | 218.2    | 12-28      | ∼3       | 30-70      | 11-18    |

Only simultaneous observations with a chance to determine the relationship in time between the various wavebands can constrain the emitting geometry. Invariably we know that RIAFs likely feed jets [20], and while LLAGN often appear as unresolved radio cores at lower resolutions, high resolution observations show that there may be jets present in all LLAGN [23].

With a luminosity ~10⁻⁹~10⁻¹⁰×L_Edd, Sgr A* is – in terms of Eddington luminosity – the weakest accreting black hole with observational statistics good enough to fit models to its spectrum. It is the primary testbed for theoretical models of extreme sub-Eddington accretion, which rely largely on the available radio/submm/NIR/X-ray observations of Sgr A* [21].

The nearby spiral galaxy M81 (NGC 3031) is an Sb spiral galaxy similar to the Milky Way. It is located at a distance of 3.63 ± 0.34 Mpc [15]. From spectroscopic measurements of the Hα + [NII] emission, probably emitted from a rotating gas disk inclined at an angle of 14° ± 2°, a mass of 7.0_{-1.5}^{+2.3} × 10⁷ M☉ could be determined for the central black hole in M81 [8]. Due to its proximity and due to its luminosity M81* is the ideal bridge between the extremely faint Sgr A* at the one extreme and AGN/Quasars on the other extreme of the luminosity scale. Intriguingly, M81* shows many similarities to Sgr A*, such as a slightly inverted radio spectrum [26] where circular polarization dominates over linear polarization at radio frequencies of 4.8~15 GHz [3, 4].

VLBI observations have revealed a stationary core with a variable one-sided jet of ~3600 AU length [2].

Sgr A* is the best example that a highly variable source can only be understood well through simultaneous measurements at different wavelengths [11, 18, 9, 10]. An international, coordinated, multi-wavelength campaign was set up in 2005-2006 in order to observe M81* simultaneously from radio wavelengths to the X-ray domain, involving instruments such as the GMRT, the VLA, the PdBI, the SMA, and the Chandra X-ray observatory (S. Markoff et al., in preparation). In this contribution we describe the result of three epochs of simultaneous observations of M81* at wavelengths of 3 and 1 mm with the Plateau de Bure interferometer that were obtained during the coordinated campaign.

2. Observations

M81* was observed with the PdBI on 24 February, 14-15 July, and 19-20 July 2005 (see Tab. 1). Phase calibration was performed with the sources 1044+719 and 0836+710. Primary flux calibrators to determine the efficiencies of the antennae were the sources 1044+719 for February 23-24 (1.6 Jy at 3 mm/1.1 Jy at 1 mm), 1044+719 (1.8 Jy at 3 mm) and 2200+420 (8.7 Jy at 1 mm) for July 14/15, and MWC349 (1.0 Jy at 3 mm) and 3C454.3 (33.0 Jy at 1 mm) for July 20. The phase calibrators 1044+719 and 0836+710 were used to fit the time-dependent fluctuations of the amplitude for all baselines. The quality of the February data is highest as concerns stability and rms of phase and amplitude (see Tab. 1). A detailed description of the data and their reduction can be found in Schödel et al. (2006, submitted to A&A).

Individual scans of 20 min duration were extracted from the calibrated data. The flux of the
sources was determined via fitting of a point source (fitting a Gaussian resulted in very similar results). The resulting light curves for M81* and the two phase calibrators are shown in Figs. 1 and 2.

3. Results
The light curves in Figs. 1 and 2 show that M81* is a continuously varying source at the observing wavelengths of 3 and 1 mm, as has been found before at 3 mm [27]. The three epochs of simultaneous measurements show in summary

- Continuous and strong ($\geq 30\%$) variability of M81*, with the largest variability at the higher frequency.
- Variability at the two wavelengths appears to be correlated.
- With increasing flux the spectral index appears to become more negative, i.e. the general trend of the spectrum becomes steeper with higher flux density at 3 mm.
- $\geq 5\sigma$ variability of the flux density occurs on time scales of 5 hours (data from February 24), or even faster (data from July 14, which are unfortunately of much lower quality).
As discussed in Schödel et al. (2006, submitted to A&A), the detected variability cannot be due to polarization of the source, which shows absence or at least a very low degree of linear polarization at the observing wavelengths [4].

4. Discussion
The simultaneous flux density measurements of M81* at 3 and 1 mm, obtained at three different epochs indicate that the flux at 1 mm is generally lower than at 3 mm, with the exception of the first $\sim 4$ hours of the 24 February light curve. This is in good agreement with previous mm-observations [26], that were, however, not acquired simultaneously.

When combining our measurements with all other radio/mm observations of M81* that have been acquired so far, we find that the highest flux densities were usually measured at a wavelength of $\sim 3$ mm [27, 6, 7, 17, 1]. The flux density measurements at shorter wavelengths by [26] and in this work may therefore indicate a decrease towards higher frequencies.

However, the evidence for a turnover in the SED of M81* between 3 and 1 mm is not unambiguous. In fact, observations with the SMA at 345 GHz that were obtained during the coordinated campaign on M81* indicate that the flux density of M81* increases toward the submm regime, in agreement with the theoretical predictions (Markoff et al., in preparation). Unfortunately, there was only one epoch (24 February 2005), where measurements with the PdBI and the SMA were simultaneous.

A jet is known to exist in M81* [2]. In a simplified jet model the turnover frequency, $\nu_t$, scales with the jet power, $Q_j$, and mass of the black hole, $M_{BH}$, like $\nu_t \propto Q_j^{2/3} M_{BH}^{-1}$ [13]. When using this relationship to compare M81* with Sgr A* one expects a $\sim 50$ times higher $\nu_t$ for M81*. Hence, while the SMA observations and theory indicate a $\nu_t$ located at submm frequencies (see also Markoff et al., in preparation), the discussion above shows that the 3 and 1 mm data by itself in combination with older data indicate a turnover at lower frequencies. The situation appears therefore somewhat complex.

Possibly, the variability of M81* at radio to mm-wavelengths is related to the ejection of plasma blobs and their subsequent adiabatic expansion [28], which would lead naturally to a stronger variability at shorter wavelengths, in agreement with the observations presented in this work. Events of adiabatic expansion of plasma blobs, that may flow outwards in a jet, would explain a negative 3-to-1 mm spectral index when the 3 mm flux is near its peak emission. In fact, the coordinated observations of M81* show some evidence for variability events that move toward longer wavelengths. Therefore, the overall peak of the emission of M81* may well be located at wavelengths shorter than 1 mm, while observations at individual epochs can indicate turnover at greater $\lambda$ because of “waves” of variability that move along an expanding outflow.
The drop-off between 07:00 UT and 12:00 UT in the highest quality data set from 24 February 2006 shows that $\sim 5\sigma$ variability of the flux at 3 and 1 mm occurs on a time scale of 5 hours. This corresponds to an upper limit on the size of the source of merely $\sim 25$ Schwarzschild radii, when a mass of $7.0 \times 10^7 M_\odot$ is assumed for the black hole in M81*. The first four data points on 14 July at 1 mm indicate a possibly even faster variability. The facts that the phase calibrators show only apparently random variations at this time and that the 3 mm light curve decreases, too, support this view. However, due to the low quality of the 14 July data, the existence of such rapid variability needs to be confirmed by additional observations. This rapid variability may be a phenomenon similar to the mm-flares seen in observations of Sgr A* [19] emphasizing again the similarity between the two sources.

The discussion above demonstrates the necessity of observing highly variable sources, such as M81*, simultaneously at different wavelengths. There is clearly an urgent need for more data of this kind. Expanding this work to other LLAGN will provide the necessary constraints for models to describe the dominant mechanisms at work in black holes that accrete in the highly sub-Eddington regime and show whether there exists indeed a scaling law for the sub-Eddington accretion from XRBs to high-mass LLAGN.

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