New Frontiers in Black Hole Astrophysics
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Similarity and diversity of black holes - view from the Very High Energies

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Abstract. Active galactic nuclei, hosting supermassive black holes and launching relativistic jets, are the most numerous objects on the gamma-ray sky. At the other end of the mass scale, phenomena related to stellar mass black holes, in particular gamma-ray bursts and microquasars, are also seen on the gamma-ray sky. While all of them are thought to launch relativistic jets, the diversity even within each of these classes is enormous. In this review, I will discuss recent very high energy gamma-ray results that underline both the similarity of the black hole systems, as well as their diversity.

Keywords. very high energy gamma-rays, active galactic nuclei, tidal disruption events, microquasars, gamma-ray bursts

1. Introduction

The known black hole systems cover both stellar mass and supermassive black holes. In Active Galactic Nuclei, the activity is driven by the accretion of matter to supermassive black hole in the centre of the galaxy. In inactive galaxies the black hole may occassionally shine up due to tidal disruption events, which occur when a star gets too close to the supermassive black hole and is bulled apart by the black hole's tidal forces. In extreme and rare cases (only two have been observed Cenko *et al.* 2012, Komossa 2015) this launches a collimated jet of particles. On stellar black hole mass scales, the microquasar phenomenon consists of a black hole feeding from companion star and launching a jet. Finally, we assume that long gamma-ray bursts are death crowls of massive stars, creating a black hole and collimated jets of particles.

The common astrophysical ingredients of these systems, the spinning black hole, the accretion disk, and the collimated jets of particles have led several scientists to look for similarities among the different systems. What properties simply scale with the black hole mass and could this be signature of something fundamental? For example, in the early work by Merloni *et al.* (2003) a fundamental plane of black hole activity was established, when the authors found that active galaxies and galactic black holes lie on a plane in three dimensional space (radio luminosity, X-ray luminosity and mass of the black hole). More recently, Nemmen *et al.* (2012) found that jets created by black holes maintain the same coupling between the total power carried by the jet and power radiated away. In our work, we have investigated if the jets of blazars and microquasars are similar in terms of outbursting mechanism and jet parameters that can be derived from the decomposition of the radio to optical light curves (Türler *et al.* 1999). We found that indeed the outburst of the microquasars and quasars are well described by shock-in-jet model, and that the jet parameters derived were rather similar for both types of systems (Türler & Lindfors 2007).

In recent years, astroparticle physics has opened new observational window to black hole systems and during our symposium we heard several interesting presentations coming from this community. Very High Energy (VHE, $E > 100\,GeV$) γ-ray experiments have revealed > 170 astrophysical sources, and black hole systems are well represented among these sources. IceCube has started the era of neutrino astronomy with the discovery of neutrinos of astrophysical origin (Aartsen *et al.* 2013) and while their origin is still unknown, black hole systems are certainly among the candidates. Finally, the LIGO experiment measured gravitational waves from merging black holes (Abbott *et al.* 2016). In this paper, I concentrate on the new observations of black hole system in the very high energies, covering the observations of active galactic nuclei, tidal disruption events, microquasars and gamma-ray bursts.

2. Supermassive black holes at very high energies

2.1. *Active Galactic Nuclei*

Active galactic nuclei (AGN) are the most numerous sources on the extragalactic VHE γ-ray sky. However, there is quite some diversity among this population. The most numerous ones are blazars, a type of active galactic nuclei, where the relativistic jet points very close to our line of sight. The blazars divide into several subcategories, all of which are seen at the VHE γ-ray sky. Furthermore, also several radio galaxies are detected.

Blazar spectral energy distribution (SED) shows two bumps, the low energy bump extends from radio to ultraviolet–X-rays while the high energy bump extends from X-rays to VHE γ-rays. The low energy emission is synchrotron emission by the electrons spiralling in the magnetic field of the jet, while the high energy emission is in most cases inverse Compton emission. The location of the synchrotron peak is used to divide the blazars in sub-categories. The sources having the peak at UV-X-ray energies are the most numerous sources in the extragalactic VHE γ-ray sky, but nowdays also low synchrotron peaking objects have been detected.

Blazars are variable in all wavelengths from radio to VHE γ-rays in timescales ranging from minutes to years. While short timescale variability is expected, as the jet is pointing so close to our line of sight, it becomes challenging when the timescales are

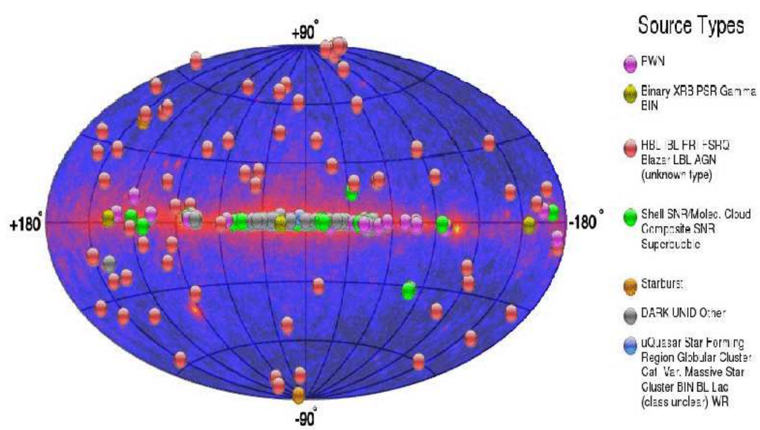

Figure 1. The Very High Energy gamma-ray sky. The map from http://tevcat.uchicago.edu.

as short as minutes. However, current instruments have observed minute-scale variability in VHE γ-rays from several sources, from all blazar classes and also from a radio galaxy (Aharonian *et al.* 2007, Albert *et al.* 2007a, Aleksic *et al.* 2011, Arlen *et al.* 2013, Aleksic *et al.* 2014a).

The minute-scale variability is challenging for models, as a huge energy has to be radiated within an extremely compact region. The time scale is actually shorter than the scale expected from the central black hole's horizon (which for $10^9 M_{sun}$ black hole is an order of one hour). Furthermore, it is a challenge for particle acceleration and emission models. Many solutions to this dilemma has been suggested, such as strong recollimation of the jet or very compact region embedded within large scale jets (spine-sheath, jets-in-jet, ring-of-fire) (e.g. Ghisellini *et al.* 2005, Giannios *et al.* 2009, MacDonald *et al.* 2015).

In many cases the fast VHE γ-ray variability is detected during periods when the source has been showing enhanced flux levels in all wavebands already prior to the detection of the fast variability. It is therefore evident that these events somehow connect to the overall activity within the relativistic jet. In the particular case of flat spectrum radio quasars, it is also evident that the VHE γ-ray emission cannot originate very close to the central black hole, as it is surrounded by broad line emission clouds (at the distance of $\sim$1 parsec) that are very efficient in absorbing VHE γ-rays via pair production (e.g. Böttcher & Els 2016 and references therein).

One particularly interesting case of fast variability is radio galaxy IC 310 in Perseus cluster. MAGIC Telescopes detected a huge flare in the VHE γ-ray band in November 2013. The flux reached several Crab Units, and the light curve revealed variability with doubling timescales faster than 4.8 minutes (Aleksic *et al.* 2014a). As the viewing angle of the jet is rather well constrained to $10-20$ degrees, the general solution of introducing $\Gamma > 50$ to explain the fast variability does not work. In general it was concluded that models, where such a bright flare with such fast variability would be produced within the jet, were not viable. Therefore it was suggested that the flare actually originated in the magnetosphere of the black hole and it was dubbed a black hole lightning. The magnetospeheric model for IC 310 was discussed in detail in Hirotani & Pu (2016), who concluded that it is feasible to produce the observed flare if the black hole at the time of

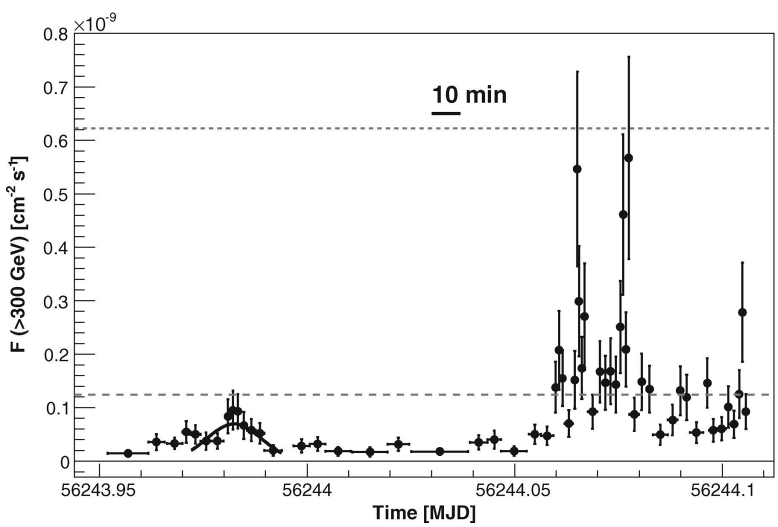

Figure 2. The light curve of IC 310 on the night of 12/13 November 2012 as observed with the MAGIC telescopes. Figure from Aleksic *et al.* 2014a.

the flare was accreting at very low rate. The feasibility of this model was discussed also during the symposium (see Barkov, this volume).

Beyond the fast variability of VHE γ-rays, also the slower timescale variability of the VHE emission, the shape of the VHE γ-ray spectrum and in more general terms the population of active galaxies that we see at the highest energies tell us important stories about supermassive black holes. Looking at the variability of the light curves in different bands as well as the snap-shot spectral energy distributions have shown that the emission takes place in multiple emission regions within the relativistic jets (e.g. Aleksic *et al.* 2014b, Aleksic *et al.* 2015a, Lindfors *et al.* 2016). It has also been shown that, at least occasionally, the main energy dissipation region must move further out in the jet, at least to distances beyond the broad line region clouds (Ghisellini *et al.* 2013, Aleksic *et al.* 2014c, Ahnen *et al.* 2015).

2.2. *Tidal Disruption Events*

In addition to AGN, the VHE γ-ray telescopes have been pointed to a normally inactive supermassive black hole, to the famous tidal disruption event Sw 1644+57. Bloom *et al.* (2011) and Burrows *et al.* (2011) argued that this event arose from the activation of a beamed jet that was hypothesized to be the result of a tidal disruption of a star by a $\sim 10^6 - 10^7 M_\odot$ black hole.

The VERITAS Telescopes started observing Sw J1644+57 approximately 22.5 hours after the first BAT trigger and followed it for 18 days (Aliu *et al.* 2011). The MAGIC telescopes observed the Sw J1644+57 during the flaring phase, starting observations nearly 2.5 days after the trigger time (Aleksic *et al.* 2013). Neither of the telescopes found evidence for emission above the energy threshold of 100 GeV and the upper limits were in agreement both with the synchrotron and inverse Compton scattering scenarios for the X-ray emission (Aliu *et al.* 2011, Aleksic *et al.* 2013). However, in principle the VHE γ-ray observations can be very constraining for the conditions of the jet in such tidal disruption events, in particular for the synchrotron origin of the X-ray emission and for the lorentz factor of the newly formed jet.

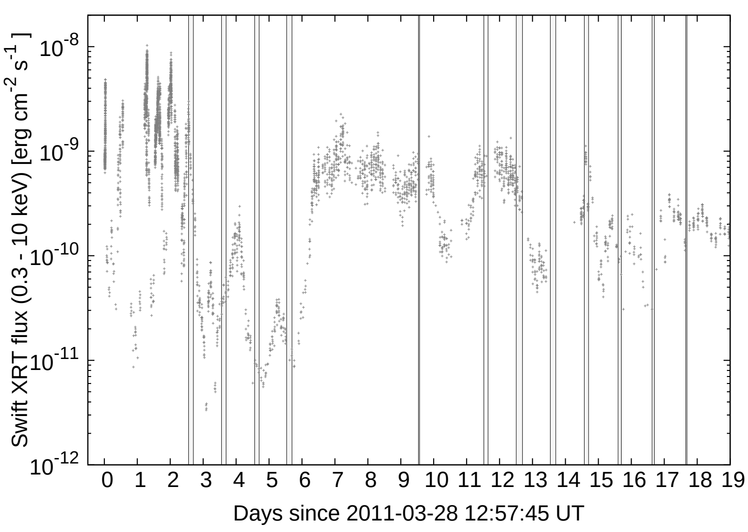

Figure 3. The light curve of Sw 1644+57 from *Swift*-XRT. The MAGIC observation windows of the event are shown as vertical lines. MAGIC detected no VHE γ-rays from this TDE. Figure from Aleksic *et al.* 2013.

In addition to Sw 1644+57, only one other possible case of jetted tidal disruption event is known (Cenko *et al.* 2012, Komossa 2015), but to my knowledge it was not followed by the VHE γ-ray telescopes.

2.3. *Supermassive black hole in the centre of our Galaxy*

Galactic center is a strong and well established source of VHE γ-rays (Aharonian *et al.* 2004, Albert *et al.* 2006a, Archer *et al.* 2014). It was already early suggested that the point source in the galactic centre would correspond to a central black hole (Aharonian *et al.* 2004), but as there are also other candidates, such as supernova remnant Sgr A East, the question of direct emission of the black hole in the center of our galaxy is not yet resolved.

Very recently H.E.S.S. Collaboration showed, using 10 years of VHE γ-ray observations of the galactic centre, that the black hole in the centre of our galaxy is the first established PeVatron, i.e particle accelerator that can accelerate particles up to PeV energies (Abramowski *et al.* 2016).

3. Stellar mass black holes at very high energies

3.1. *Microquasars*

X-ray binaries are binary systems with a compact object (a black hole or a neutron star) feeding from a companion. In microquasars this feeding launches a relativistic jet and as an analogy to more massive quasars, these jets could accelarate particles to energies high enough to emit VHE γ-rays.

There were two detections of VHE γ-ray emission from binary systems that were first considered as possible microquasars, LS5039 and LSI +61 303 (Aharonian *et al.* 2005, Albert *et al.* 2006b), but later observations have supported binary pulsar model for these sources (e.g. Albert *et al.* 2008). Up to date, the hint of VHE γ-ray emission from a microquasar Cyg X-1 (Albert *et al.* 2007b) is the only indication of VHE emission, while other observations have resulted only in upper limits (Aleksic *et al.* 2010a, Abdalla *et al.* 2016). The reason can be that the conditions are not favorable to emission of VHE γ-rays, given that it always requires acceleration of particles to extreme energies and typically also presence of photons to be up-scattered. Other possible explanation is an observational bias, as it is evident that the high energy emission from the microquasar jets is a transient phenomena.

Cyg X-1 and Cyg X-3 are both detected in the lower gamma-ray energies by the Fermi satellite and the origin of this emission seems to be the jet (Abdo *et al.* 2009, Zanin *et al.* 2016, Zdziarski *et al.* 2016). Therefore, it is to be expected that during flares the emission would extend also to energies > 100 GeV, unless the gamma-rays are always emitted very close to jet base, where strong photon field absorbing VHE γ-rays is present. If the microqusars were to be analogies to quasars, one would expect that occassionally the energy dissipation region would move further out and VHE γ-rays could escape. To catch such a epoch, which is assumably an order of an hour in duration or shorter, with ground-based telescopes (limited duty cycle and limited field of view) is of course challenging.

3.2. *Gamma-ray bursts*

Gamma-ray bursts (GRBs) launch short lived, but extremely fast and luminous jets. As the duration of the prompt emission from GRBs is typically an order of a minute or less, fast pointing to the location of the GRBs is in a key role. Up to now there is no detection of VHE γ-ray emission from GRBs by the Imaging Air Cherenkov Telescopes (Albert *et al.* 2006c, Tam *et al.* 2006, Albert *et al.* 2007c, Aharonian *et al.* 2009,

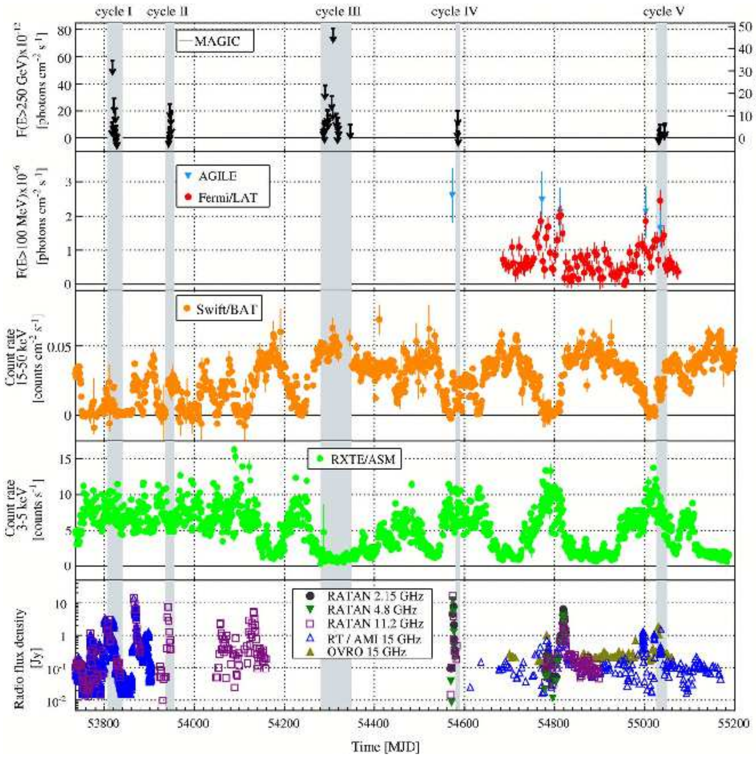

Figure 4. The light curve of Cyg X-3 as observed with the MAGIC telescopes (top), textitFermi-LAT and AGILE satellites, *Swift*-BAT, RXTE-ASM and OVRO and AMI telescopes (bottom) from 2006 to 2009. The gray band show the periods corresponding to MAGIC observations. The MAGIC observations covered different X-ray/radio spectral states. No VHE γ-ray emission from the source was detected. Figure from Aleksic *et al.* 2010a.

Aleksic *et al.* 2010b, Acciari *et al.* 2011, Aleksic *et al.* 2014d), but the detection of high energy photons by the *Fermi*-LAT from some GRBs (e.g. Ackermann *et al.* 2014) certainly gives hope also to ground-based experiments. VHE γ-ray observations are a powerful tool for emission processes and physical conditions in GRBs and could also give important insight on the similarity of the emission processes in GRB and blazar jets.

4. Summary

Phenomena related to black holes at VHE γ-rays are mostly transient or extremely variable and therefore a huge observational challenge. As this window to black hole systems is still rather new, there are many open questions and also significant discovery potential in this energy range. The most prominent black holes at VHE γ-rays are the active galactic nuclei, where we have already started to see diversity as the number of known sources is steadily increasing (currently > 70). For the rest; tidal disruption events, microquasars and gamma-ray bursts, we will have to wait for further observations at VHE γ-rays, with the current generation of telescopes and with the future Cherenkov Telescope Array, to be able to say something about the similarity of the all black hole systems at very high energies.

References

M. G. Aartsen, R. Abbasi, Y. Abdou, *et al.* (IceCube Coll.) 2013, *Science*, 342, 6161

B. P. Abbott, R. Abbott, T.D. Abbott *et al.* (LIGO Coll.) 2016, *PhysRevLett*, 116, id.061102

A. A. Abdo, M. Ackermann, M. Ajello *et al.* (Fermi-LAT Coll.) 2009, *Science*, 326, 1512

H. Abdalla, A. Abramowski, F. Aharonian *et al.* (H.E.S.S. Coll.) 2016, *A&A*, accepted, arXiv:1607.04613

A. Abramowski, F. Aharonian, F. A. Benkhali *et al.* (H.E.S.S. Coll.) 2016, *Nature*, 531, 476

V. A. Acciari, E. Aliu, T. Arlen *et al.* (VERITAS Coll.) 2011, *ApJ*, 743, 62

M. Ackermann, M. Ajello, K. Asano *et al.* (Fermi-LAT Coll.) 2014, *Science*, 343, 42

F. Aharonian, A. G. Akhperjanian, K.-M. Aye *et al.* (H.E.S.S. Coll.) 2004, *A&A*, 425, 13

F. Aharonian, A. G. Akhperjanian, K.-M. Aye *et al.* (H.E.S.S. Coll.) 2005, *Science*, 309, 746

F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi *et al.* (H.E.S.S. Coll.) 2007, *ApJ*, 664, 71

F. Aharonian, A. G. Akhperjanian, U. Barres *et al.* (H.E.S.S. Coll.) 2009, *ApJ*, 690, 1068

M. Ahnen, S. Ansoldi, L. A. Antonelli *et al.* (MAGIC Coll.) 2015, *ApJ*, 815, 23

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2006a, *ApJ*, 638, 101

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2006b, *Science*, 312, 1771

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2006c, *ApJ*, 641, 9

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2007a, *ApJ*, 669, 862

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2007b, *ApJ*, 665, 51

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2007c, *ApJ*, 667, 358

J. Albert, E. Aliu, H. Anderhub *et al.* (MAGIC Coll.) 2008, *ApJ*, 684, 1351

J. Aleksic, L. A. Antonelli, P. Antoranz *et al.* (MAGIC Coll.) 2010a, *ApJ*, 721, 843

J. Aleksic, L. A. Antonelli, P. Antoranz *et al.* (MAGIC Coll.) 2010b, *A&A*, 517, 5

J. Aleksic, L. A. Antonelli, P. Antoranz *et al.* (MAGIC Coll.) 2011, *ApJ*, 730, 8

J. Aleksic, L. A. Antonelli, P. Antoranz *et al.* (MAGIC Coll.) 2013, *A&A*, 552, 112

J. Aleksic, S. Ansoldi, L. A. Antonelli *et al.* (MAGIC Coll.) 2014, *Science*, 346, 1080

J. Aleksic, S. Ansoldi, L. A. Antonelli *et al.* (MAGIC Coll.) 2014, *A&A*, 567, 135

J. Aleksic, S. Ansoldi, L. A. Antonelli *et al.* (MAGIC Coll.) 2014, *A&A*, 569, 46

J. Aleksic, S. Ansoldi, L. A. Antonelli *et al.* (MAGIC Coll.) 2014d, *MNRAS*, 437, 3103

J. Aleksic, S. Ansoldi, L. A. Antonelli *et al.* (MAGIC Coll.) 2015, *A&A*, 578, 22

E. Aliu, T. Arlen, T. Aune *et al.* (VERITAS Coll.) 2011, *ApJ*, 738, 30

T. Arlen, T. Aune, M. Beilicke *et al.* (VERITAS Coll.) 2013, *ApJ*, 762, 92

A. Archer, A. Barnacka, M. Beilicke *et al.* (VERITAS Coll.) 2014, *ApJ*, 790, 149

J. Bloom, D. Giannios, B. Metzger *et al.* 2011, *Science*, 333, 203

D. N. Burrows, J. A. Kennea, G. Ghisellini *et al.* 2011,

M. Böttcher & P. Els 2016, *ApJ*, 821, 102

S. B. Cenko, H. A. Krimm, A. Horesh 2012, *ApJ*, 753, 77

G. Ghisellini, F. Tavecchio, M. Chiaberge 2005, *A&A*, 432, 401

G. Ghisellini, F. Tavecchio, L. Foschini *et al.* 2013, *MNRAS*, 432, 66

D. Giannios, D. Uzdensky, M. Begelman 2009, *MNRAS*, 395, 29

K. Hirotani & H. Pu 2016, *ApJ*, 818, 50

S. Komossa 2015, *Journal of High Energy Astrophysics*, 7, 148

E. Lindfors, T. Hovatta, K. Nilsson *et al.* , 2016 *A&A*, 593, 98

N. MacDonald, A. Marscher, S. Jorstad *et al.* , 2015 *ApJ*, 804, 111

A. Merloni, S. Heinz, T. di Matteo, 2003 *MNRAS*, 345, 1057

R. S., Nemmen, M. Georganopoulos, S. Guiriec *et al.* 2012, *Science*, 338, 1445

P. H. Tamm, S. J. Wagner, G. Pühlhofer (on behalf of H.E.S.S. Coll.) 2006, *Il Nuovo Cimento B*, 121, 1595

M. Türler, T. J.-L. Courvoisier & S. Paltani 1999, *A&A*, 349, 45

M. Türler & E. Lindfors 2007, *Proceedings of IAU Symposium #238, Cambridge, UK: Cambridge University Press*, 238, 305

R. Zanin, A. Fernandez-Barral, E. de Ona-Wilhelmi *et al.* 2016, *A&A*, accepted, arXiv:1605.05914

A. A. Zdziarski, D. Malyshev, M. Chernyakova *et al.* 2016, *MNRAS*, submitted, arXiv:1607.05059