THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

RADZIKOWSKIEGO 152
31-342 KRAKÓW, POLAND

SWITCHBOARD: +48 12 662 8000
DIRECTOR: +48 12 662 8200
FAX: +48 12 662 8458

www.ifj.edu.pl
press@ifj.edu.pl

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Two decades of blazar observations, and the mysteries keep piling up

Narrow jets of luminous matter may be emitted towards Earth from the nuclei of active galaxies, billions of light-years away. The galaxy then appears as a point source and is called a blazar. A Polish-German team of scientists has, for the first time, analysed the activity of one such blazar over a long period of time and instead of finding answers, they have been faced with an ever-increasing number of intriguing questions.

Distant, active galaxies that emit jets of matter at small angles towards Earth, known as blazars, present astronomers with numerous observational and interpretative challenges. Their immense distance and specific orientation, combined with the high variability of the emitted radiation – which, moreover, is generated across a very wide energy range – are the main reasons why understanding the phenomena responsible for the properties of blazars is particularly difficult. Are the current interpretations of the nature of these objects, based on short-term and rather sporadic observations, correct? A group of scientists from the University of Heidelberg and the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow set out to answer this question. The research carried out on the Polish side, funded by a grant from the National Agency for Academic Exchange, focused on the blazar PKS 2155-304, located one and a half billion light-years away. It is situated in the southern celestial hemisphere, in the background of the constellation *Piscis Austrinus*.

Hundreds of billions of galaxies have already been discovered within the observable Universe. Some of them have been found to produce vast amounts of electromagnetic radiation, probably as a result of violent processes occurring as matter falls into a central supermassive black hole. The activity of some such galaxies takes on a particularly spectacular form: jets – narrow streams of ionised, luminous matter – shoot out from the vicinity of the black hole's poles, sometimes extending for as far as tens of millions of light-years. Astronomers refer to active galaxies with jets pointing towards Earth as blazars. Blazars generate radiation across a very wide energy range, from radio waves through the optical and ultraviolet regions to X-rays and gamma rays.

"The variability of blazars is a characteristic feature that has long been recognised. Blazars are capable of emitting radiation not only in different ways during different observations, but even within the same observation, when variations in some energy ranges may differ from those in others," notes Dr. Alicja Wierzcholska (IFJ PAN), lead author of the long-term analyses of observations of the blazar PKS 2155-304.

Observations of blazars have been carried out for several decades, but it would be difficult to describe them as precise monitoring. In the case of such variable objects, it would be necessary to use numerous instruments capable of detecting electromagnetic radiation across virtually the entire energy spectrum, and ideally on a continuous basis, at least for selected objects. However, such observatories simply do not exist at present. The reality is therefore that individual blazars are usually observed every few months or years, as part of campaigns lasting no more than a few to a dozen or so days, and the data collected relate to their activity only within narrow energy ranges of radiation detected by a specific instrument.

The present analysis covered measurements taken over a much longer period – almost two decades. The data, which complemented one another in terms of energy ranges, were obtained from the US satellite observatories: the Neil Gehrels Swift Observatory (in the optical, ultraviolet and X-ray ranges) and the Fermi Gamma-ray Space Telescope (in the gamma-ray range).

“The key conclusion from our analyses is that the currently most popular theoretical models, which assume that radiation is emitted within a single jet zone by a single population of electrons, can only describe the variability of our blazar over short time scales. However, something more complex is clearly happening in this object, which short observation campaigns are unable to capture,” says Dr. Wierzcholska.

An example? Intuition suggests that if the source of emission in the optical and X-ray ranges were the same population of electrons, changes in one part of the spectrum should be correlated with changes in the other, perhaps with a slight time delay. However, the analysed data failed to reveal any long-term correlation between events in different radiation ranges.

When blazars brighten rapidly in the X-ray range, the rule generally holds that the increase in brightness is more pronounced in the higher-energy part of the spectrum. In other words, during a flare, more hard X-ray photons are observed than during periods of low blazar activity. In the case of PKS 2155-304, this behaviour has not been observed over 20 years of monitoring. Such a correlation is visible for shorter observation periods, but it is of a different nature (the curves depicting changes in the distribution have different slopes). This fact suggests that slightly different physical mechanisms must be responsible for the course of each outburst of PKS 2155-304.

That was not the end of the surprises. The graphs showing the full energy spectrum of blazars have an interesting feature: they reveal two ‘peaks’ separated by an arched trough. The low-energy peak appears to be caused by electrons and the synchrotron radiation they emit, whilst there is no clear explanation for the high-energy peak. This may be the result of collisions between electrons and low-energy photons, leading to an increase in the photons’ energy (i.e. inverse Compton scattering), but it cannot be ruled out that it stems from phenomena involving hadrons – that is, quark aggregates such as protons or neutrons. However, in the case of two observations from 2012, something particularly strange appeared in the spectrum of PKS 2155-304: an additional, statistically significant dip.

“The presence of a new inflection in the blazar’s spectrum tells us that some additional physical mechanism must have been at work between the two observations – and this at a time when there was no outburst! Various theoretical considerations suggest that this mechanism was most likely hadronic in nature. This is extremely interesting, as theorists are increasingly arguing that neutrino production is possible in such situations,” explains Dr. Wierzcholska.

Neutrinos are particles with very small masses that fill the Universe in vast numbers. However, their presence is difficult to detect because they interact very weakly with ordinary matter. In the Earth’s environment, neutrinos produced during radioactive decays deep within the Earth, those arriving from the Sun, and high-energy neutrinos from deep space are observed. The origin of the latter is not entirely clear to astrophysicists. There are both theoretical and observational indications – in particular, the detection of neutrinos arriving from the direction of the blazar TXS 0506+056 during a powerful outburst from this source – that it is blazars that may be responsible for the emission of cosmic neutrinos.

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ics. In 2017, the European Commission granted the Institute the HR Excellence in Research award. As a result of the categorization of the Ministry of Education and Science, the Institute has been classified into the A+ category (the highest scientific category in Poland) in the field of physical sciences.

CONTACTS:

Dr. **Alicja Wierzcholska**
Institute of Nuclear Physics, Polish Academy of Science
tel.: +48 12 6628274
email: alicja.wierzcholska@ifj.edu.pl

SCIENTIFIC PUBLICATIONS:

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LINKS:

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The website of the Institute of Nuclear Physics, Polish Academy of Sciences.

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Artist's impression of a blazar – an active galaxy emitting jets of radiation and matter towards Earth. (Source: NASA/JPL-Caltech)