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# AGN astrophysics from comparing radio and Gaia optical astrometry

## Relativistic jets and gravitational wave rockets

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**Abstract.** Gaia will open up a huge volume of new parameter space in which to explore the physics of AGN and black hole evolution. We address the question as to how far along the relativistic jets blazar radio, optical and gamma ray emission originated. In some models the optical centroid wander should be detectable as the relative contributions of thermal and non-thermal optical emission change. Black holes powering AGN do not necessarily reside at the centres of their host galaxies; they can be one member of a binary pair or they could have received a kick after binary coalescence. In radio-loud AGN comparison of astrometric radio and and optical positions can reveal such displacements. It is suggested that it would be feasible to do this using Gaia and e-MERLIN for a sample of thousands of elliptical radio galaxies.

**Key words.** Galaxies: active – Galaxies: astrometry – Galaxies: radio

### 1. Introduction

There are numerous ways in which the combination of Gaia optical astrometry and accurate radio astrometry can be used to investigate important astrophysical questions. Several of these are covered in detail in other contributions to the meeting. I will focus primarily on two questions: the physics of radio jets, in particular where does the radio emission arise with respect to the central black hole, and searching for AGN displaced from the centres of their host galaxies, either because there is a binary black hole or the black hole has received a large velocity kick as a result of the coalescence of two black holes. Though there may be recognizable electromagnetic signatures for kicked black holes (see Komossa (2012) for a recent review), astrometry offers the only possibility for unambiguous detections.

### 2. The astrophysics of radio jets

We start by summarizing what we think we know about radio jets and then discuss open questions which might be addressed astrometrically.

– Jets are produced by accreting black hole systems
– They are emitted in opposite directions with relativistic speeds having bulk Lorentz factors ranging up to 10 or 20 and

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perhaps more. For this reason it is nearly always only the approaching jet that is visible
- At all wavelengths jets flare on a range of timescales of weeks to many years
- Using VLBI, superluminal motion of blobs in the jets is detected and the emergence of new moving blobs appear to be related to flaring activity.
- The radio, infrared, optical, and sometimes X-ray emission, is produced by the synchrotron mechanism. The jets have a secondary peak in their spectral energy distributions which is usually attributed to inverse Compton emission. Surveys of the high latitude sky are dominated by the same objects at gamma-ray frequencies as at GHz frequencies.
- The optical and gamma ray emission seems to come from the same part of the jet. This conclusion is based on evidence that there is a correlation with no appreciable time delay (Wagner & Hauser 2011) between optical and gamma-ray flare activity. Similarly, comparison of multi-epoch VLBI data and gamma-ray variability suggest that in many cases the radio and gamma-ray emission regions are co-spatial.

We can be reasonable confident of most of the above. Astrometry is unlikely to have direct impact on the really big issue of the mechanism of jet production. There are, however, important secondary questions concerning where things happen that are certainly in the realm of astrometric investigation. The answers to these should give indirect pointers to jet production physics. We would like to know from where the non-thermal jet emission at all wavelengths originates relative to the thermal AGN emission the latter being the best marker we have for the position of the black hole.

There is an active debate concerning the location all the non-thermal emission. On the one hand Marscher (2011), Agudo, et al. (2011) and Jorstad et al. (2011) present convincing observational evidence for this emission occurring ∼10 pc or more downstream from the jet origin. On the other hand Stern & Poutanen (2011) present strong theoretical arguments for the gamma-ray emission originating within the BLR; i.e ∼0.1 pc from the jet base. Which of these scenarios is correct, or if both are correct in the sense the position of the emitting regions is different in different types of object, has knock on consequences. For example, the density of AGN thermal photons in the non-thermal emitting region will depend on how far downstream the latter is. This is important because there is a debate concerning the relative importance of internally generated photons and external AGN photons in the production of the gamma-ray emission (Gupta et al. 2011).

How can astrometry help? At z = 1, a typical quasar redshift, 1 mas is about 8 pc and hence well within the realm to be probed by Gaia astrometry. Imagine a flat spectrum radio quasar (FSRQ) in which the contributions to the total emission of the blazar and the thermal disk are roughly equal. If the blazar emission originates ∼10 pc away from the core and the blazar component varies, then the centroid of the combined emission will shift up and down the jet. Thus finding optical centroid shifts, especially of the position shifts correlated with the brightness of an object would be a strong support for the scenario in which the non-thermal emission regions were well outside the BLR (see contribution of Sonia Anton). Further support would be forthcoming if the direction of shift was found to be along the jet axis as determined from VLBI. More direct comparison of VLBI radio positions and Gaia optical ones are covered in other contributions. This kind of comparison can tell us directly if the jet non-thermal optical and radio emission originate from the same place but not where both occur relative to thermal emission arising from accretion on to the black hole.

## 3. Searching for displaced black holes

The idea is to pick a large sample of passive elliptical galaxies which have detectable compact radio emission and look for displacements between the centroid of the stellar light as measured with Gaia and the centroid of the radio emission. The basic premise is that the stellar light will define the centre of mass and the radio emission the position of the black hole. The radio astrometry could be done with $\sim$1 mas precision using the e-MERLIN array in the UK. Significant displacements could arise due to either a binary black hole system with only one black hole powering a radio source or a "kicked" black hole after the coalescence of a binary black hole system before the merged black hole settles back to the centre of mass (Fatava et al., 2004).

There is an extensive literature on the life cycle of black holes during the hierarchical merging process that has built the galaxies we see today (e.g. Volonteri et al. 2010; Baker, et al. 2008). In a seminal paper by Begelman et al. (1980) they describe how after galaxies merge, their associated nuclei which consist of a central stellar cluster and black hole, rapidly merge and a binary black hole system forms in the new enlarged stellar cluster. Dynamical friction shrinks the orbit on a timescale of $\sim 10^8$ yr at which point most of the stars that contribute the dynamical friction are depleted and the orbit can "stall" at a radius $\leq$1 pc. How long this stalled phase lasts is very uncertain but is very relevant to the redshift when most black hole coalescences occur. If it is the order of a Hubble time many coalescences should be happening at the present epoch but if much shorter most will have happened at a much higher redshift near the epoch at which the galaxy merger rate peaks.

Though the Begelman et al. (1980) analysis gives good description of the period up to black hole coalescence it is only in the last few years that numerical general relativity has been able to treat the actual coalescence phase. The prediction of the emission of a burst of gravitational radiation is expected and well known. What is new and remarkable is that under the right initial conditions the single black hole produced in the process receives a large kick in velocity, occasionally greater than the escape velocity of the galaxy, but often large enough to be detected (Fatava et al., 2004).

Both binaries and kicked black holes could give rise to detectable displacements of an active nucleus from the centre of mass of the host galaxy. There are many imponderables influencing how likely one is to detect measurable displacements. Various characteristic timescales are important:

1. The length of time that it takes for a pair of black holes to reach stalling orbit after their parent galaxies merge. It is only during this pre-stalled phase that the separation will be large enough to be detected.
2. The length of time the orbit remains stalled. If this is short most coalescences will happen at high redshift when the merger rate is greatest.
3. If a kick is given when the black holes coalesce, how long is it before the black hole settles down to the centre of mass.

The primary motivation for a search for binary and kicked black holes is to try and pin down these times and timescales. The time after host galaxy merger and the associated black holes reaching stalling radius is expected to be $\sim 10^8$ yr, thus perhaps a few percent of high redshift galaxies may host binary black holes with orbital radii $\geq$1 pc. In how many there might be detectable radio emission from at least one of the black holes is very uncertain though the existence of two detectable radio nuclei in 0402+379 with a separation of 7.3 pc (Rodrigues et al. 2006) is encouraging. On the other hand in a search of 3114 sources with VLBI maps was made by Burke-Spolaor (2011). She was looking for multiple nuclei with separations $\leq$100 mas and 0402+379 was the only binary black hole candidate detected. Thus the occurrence of two orbiting black holes both of which are radio loud is rare.

No double radio nuclei with wider separations were found in the $\sim$ 16000 200 mas-resolution radio maps made during the CLASS gravitational lens search (Browne, et al. 2003). On the other hand we are talking about the probability of both black holes being active radio sources. If we, for example, take it that the statistics indicate that perhaps one in 10,000 radio sources have two radio nuclei, then, a perhaps reasonable guess would be that 1 in 100 might have one of the pair radio loud. The fundamental problem in the case of a single radio loud nucleus is finding a position reference with respect to which the black hole can be measured. The position reference problem can be solved in principal for passive elliptical galaxies because the starlight can be used as a proxy to estimate the position of the centre of mass (see below).

Estimating the likelihood of being able to detect kicked black holes is probably even more uncertain than that for binary black holes. The stalling time before coalescence is not well constrained. However, it is believed that after coalescence the timescale for the kick hole to settle back to the centre of the merged galaxy is also $\sim 10^8$ yr. But we do not know if the black hole will be capable of powering a radio source during this time. Simulations have been performed by Sijacki et al. (2011) focused on the amount of optical AGN emission expected but not of the expected radio emission. Furthermore, depending upon how long the orbits remain stalled before final coalescence will determine whether there are any black holes remaining "kicked" in the relatively low redshift universe.

Passive elliptical radio galaxies (i.e. having no optical evidence for an AGN) form the best targets. The elliptical galaxy light should define the galaxy position and the compact radio nucleus defines the position of the black hole. There are still some significant uncertainties. We do not know if kicked black holes will be (radio) active. There are, though, encouraging hints; there is a claim for a displacement detected in M87 (Batcheldor, et al. 2010).

Another practical uncertainty is how well measuring the centroid of the visible light defines the centre of mass. Tidal tails, twisting isophotes and faint companion galaxies could all cause problems. A pilot study should be done. Because real black hole displacements will be the exception rather than the rule a sample of a few tens of radio ellipticals with the best available ground-based astrometry should be picked and the positions of their radio cores measured. One would hope that the spread in radio-optical position differences would be consistent with the known astrometric errors. If the results were encouraging this could lead on to a major programme to measure several thousand radio positions with e-MERLIN for comparison with Gaia optical positions. In a similar programme to the one outlined above Condon (2011) have been using a combination of VLBA observations for the radio astrometry and 2MASS for the optical astrometry and find that the displacements are consistent with the 2MASS astrometric errors. Clearly Gaia will be have much better astrometric accuracy than 2MASS.

## 4. Conclusions

Two areas where Gaia can have a major impact in questions of major importance in extragalactic astrophysics are in the physics of radio jets in blazars and on elucidating the life histories of black holes during and after galaxy mergers. In the case of blazars one would look for time-variable displacements of the radio and optical centroids and see if these displacements were correlated with variations in optical total intensity. If detected this would be good evidence for the jet emission arising $\geq$ a few parsec from the galactic nucleus.

Predictions of the hierarchical merging picture of galaxy formation are that black hole binaries should form, after a time they should coalesce and occasionally the black hole produced by the coalescence should receive a velocity kick large enough to produce a displacement of ~kpc from the centre of mass of the host galaxy. The timescales for many of these stages in the life histories of supermassive black holes are uncertain and the only way they can be constrained is by quantifying the number of binary black holes and trying to detect kicked black holes. Comparing the radio positions of compact sources with the Gaia-measured optical centroids of elliptical galaxies offers an unique opportunity to get a handle on some of these illusive numbers.

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