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Strong gravitational lensing in the radio domain

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Conclusions and future outlook

6.1 Physics behind the extrinsic variability in B1600+434

In Chapter 2, we contribute to increase the observational evidence regarding the extrinsic variability in the gravitational lens B1600+434 reported by Koopmans et al. (2000). Apart from confirming its presence over a period of four years, we have identified three different manifestations of extrinsic variability: (i) continuous fluctuations with an rms scatter of $\sim 3\%$, (ii) changes in the flux ratio of the images between the different observing seasons (separated in time by ~ 1.5 years), and (iii) two events with flux variations of 10% and 15% spanning several weeks.

The next step is to establish what is the predominant cause of these fluctuations: (i) scattering/scintillation by the ISM in the lens galaxy or/and in our own galaxy, or (ii) microlensing of a jet-component in the quasar, due to compact objects in the halo of the lens galaxy. As pointed out in Koopmans & de Bruyn (2000), the strong opposite dependence with frequency of these two physical processes provides us with a powerful tool to establish the nature of the extrinsic variability. However, validating the microlensing scenario also requires confirmation that the quasar images have a core-jet structure.

The observations required to make this kind of analysis are already at our disposal. As indicated in Chapter 2, we have VLA data in another three bands during 3-4 epochs of eight months. We also have 4 VLBA epochs at 15 GHz (spaced by about 50 days), obtained during the season in which the quasar experienced a strong outburst (season 4 observed in summer 2002, see Fig. 2.3 on page 38). Note that the VLBA observations presented in Patnaik & Kemball (2001) where made in September 2000, in a period where the quasar seemed to be in a quiet phase (between our seasons 2 and 3) . If the quasar really has a jet component, it is conceivable that it was very faint at the time of Patnaik & Kemball observations, explaining why they were not able to detect it. Our VLBA observations in season 4 might provide the key to address this question. In addition, the combined flux of both lensed images was monitored with WSRT at 4.8 GHz, 2.3 and 1.4 GHz for a period of ~ 60 days during the rise of the season 4 outburst, leading up to the 1st VLBA observations. The better sampling of these observations with respect to the VLA campaign (1-2 days compared with 3.3 days) can help to identify more strong short-term events like the two ones mentioned before.

6.2 The nature of SMM J04542−0301

Despite the fact that the work presented in this thesis has contributed substantially to our understanding of the extended sub-mm emission SMM J04542−0301 (Chapters 3 and 4), there are several questions that need to be answered in order to fully determine the nature of this system.

First of all, we need to resolve the structure of SMM J04542−0301, to establish whether the three EROs located in its faint central region (T_c, T_d and T_f, see Fig. 4.11 on page 89) and the radio source RJ (see Fig. 4.4 on page 77) are contributing to the observed sub-mm emission. Before the advent of ALMA, the only instrument capable to do this is the SMA. Thanks to the sub-arcsecond resolution that it is able to provide at 890 μm, it might be possible to resolve the sub-mm emission in the region of the optical arc, helping us to establish a stronger connection between SMM J04542−0301, the radio sources, and the optical/NIR multiple images.

The radio observations presented in Chapter 3 and 4 already provide strong evidence in favor of the merger scenario proposed by Borys et al. (2004a). However, an unambiguous confirmation of this scenario requires the redshifts of the EROs, the sub-mm emission and the radio emission. Current millimeter facilities can provide redshift information by detecting (for instance) CO rotational lines, but the relatively narrow bandwidths of their receivers (< 10 GHz compared with the 115 GHz spacing between CO rotational lines) makes the search of multiple lines very time-consuming, and a prior estimate of the redshift of the source is required. Fortunately, blind CO redshift observations are now possible thanks to Z-Spec, a broadband (~115 GHz) millimeter/sub-millimeter spectrograph that has been recently commissioned at the 10.4-m Caltech Sub-millimeter Observatory (Bradford et al. 2009).

The confirmation of the merger scenario would establish SMM J04542−0301 as a unique high-redshift laboratory to study the morphology and physical properties of an intrinsically faint sub-mm galaxy with unprecedented resolution. In fact, our radio observations indicate the presence of two compact emitting regions embedded in an extended radio source that seem to be associated with the central dust obscured region of the merger. Given its faintness, a robust detection and proper characterization of its properties will require the improved broad-band sensitivity and capabilities (such as high fidelity imaging of extended low-brightness emission) of the EVLA.

Once all the sources that are contributing to the observed sub-mm emission in SMM J04542−0301 have been robustly identified, the increased bandwidth and sensitivity of the new receivers that have been installed on the IRAM[1] 30 m telescope (located on the Pico Veleta, Spain) and the Plateau de Bure Interferometer (located in the French Alps), will be well placed to characterize the physical properties of this system in detail.

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6.3 Future Outlook

Radio observations of SMGs have been traditionally used to identify their optical/NIR counterparts, but also to provide estimates of their sizes (Chapman et al. 2004; Biggs & Ivison 2008). On the other hand, the magnification bias due to the gravitational lensing effect produced by clusters of galaxies has been used to increase the detection rate in sub-mm surveys, and constrain the faint flux end of the sub-mm counts (e.g. Knudsen et al. 2008). The observations presented in Chapter 4, however, illustrate that the prospects for both radio interferometry and strong gravitational lensing in clusters of galaxies to study the internal structure of sub-mm galaxies (SMGs) are also very promising. With the improved sensitivity of the e-MERLIN and the EVLA, and the revolutionary view of the sub-mm sky that will be provided by ALMA, the enhanced resolution of multiply-imaged SMGs might permit us, among other things, to resolve for the first time their different star-forming regions, and help to assess the connection between starburst and AGN processes that seem to coexist in these systems.

In order to follow this line of research, there are two important issues that have to be considered:

- How often are multiply imaged systems like SMM J04542−0301 observed in the sky. If they are a common phenomenon, it could be possible to make a sample of lensed faint SMGs, to obtain information about the general properties of this largely unknown galaxy population.
- Since these lensed systems consist of multiple distorted images, a reliable reconstruction of the source is essential to guarantee an accurate interpretation of the observations.

6.3.1 Gravitational arc surveys in radio and sub-mm

The reliability of source reconstruction in gravitational lens modeling depends on the amount of information that the multiple images can provide to constrain the lens potential (or the lens mass distribution). In this sense, lens systems with extended source brightness distributions, like giant arcs and Einstein rings, are the ideal systems to make this kind of studies, because they provide the largest number of constraints.

For this reason, in Chapter 5 we explore the possibilities of future systematic studies of arcs due to SMGs. This has been accomplished by making the first detailed predictions of the abundance of arcs produced by this galaxy population (both at sub-mm and radio wavelengths) as function of surface brightness.

The results indicate that the detection of a statistically significant number of arcs due to SMGs is not straightforward: it requires to find the best compromise between survey area, depth and resolution. Therefore, designing the optimal survey will benefit from predictions of arc abundances as function of both the surface brightness and the resolution of the interferometer.

On the other hand, despite the fact that our predictions have used the current observational information about SMGs, there is room for improvement. From the four ingredients required to predict arc abundances (source shape and size, source redshift distribution, source cumulative number counts and a model of the cluster population), the large uncertainty in the sub-mm number counts at fluxes fainter than 1 mJy is dominating the errors in the results. The predictions could also be improved by using a source size distribution of SMGs obtained from sub-mm observations, instead of an average size provided by radio observations. However, since the effect of source size on lensing cross sections is quite mild, we do not expect a large effect on the derived arc abundances.

6.3.2 Lens modeling and source reconstruction

In the last few years, the development of lens modeling methods for optical observations has experienced an important development thanks to the use of pixel-based image reconstruction techniques (e.g. Warren & Dye 2003; Suyu et al. 2006; Koopmans 2005; Brewer & Lewis 2006; Vegetti & Koopmans 2009a), which permit to fully exploit all the constraints provided by lens systems with extended source brightness distributions (like giant arcs and Einstein rings).

However, the use of radio and sub-mm arcs produced by SMGs to obtain information about their internal structure will require to further develop these kind of lens modeling techniques in two fronts:

- All these different methods have been implemented to study systems where the lens is a galaxy. The next step is to increase the degree of complexity by providing models of galaxy clusters that are suitable to study the lensed sources.
- Most of the work is focused on optical data. However, a combined multi-wavelength analysis of arcs and Einstein rings can provide much more constrains for the lens model than the optical data alone.

The main challenge of a full multi-wavelength approach is the intrinsic difference between single dish and interferometric observations. To date, the *LensClean* code (Wucknitz 2004) is the only lens modeling software that takes the effects of incomplete UV coverage of interferometric observations into account.