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Gravitational lensing by spiral galaxies

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Abstract. Spiral galaxies at moderate redshifts and oriented optimally could form characteristic multiple images of extended background sources from which the mass distribution in the galaxy can be estimated. The absorption profile due to the galaxy provides a reliable tool for the chemical and thermal diagnostic of the lens.

Keywords. Gravitational lens; spiral galaxy; rotation curve; absorption lines.

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1. Introduction

In general relativity, the space time curvature and the gravitational mass are related through Einstein's equations, a conseqence of which is the apparent bending and distortion of the photon path near a massive object. During the last two decades, this provided a powerful tool for confrontation of theories with observations, through gravitational lensing of a source due to an intervening massive object and formation of multiple images having identical intrinsic properties.

An object can show signatures of strong lensing, like distortion of the image into arcs or formation of multiple images, if its central projected surface mass density Σ exceeds a critical value, $\Sigma_{\rm cr} \sim c^2/(4\pi G D_{\rm eff})$, where $D_{\rm eff} = (D_l D_{\rm ls})/D_s$ and D_l, D_s, D_{ls} are the angular diameter distances from the lens to observer, source to observer and source to lens respectively. It is clear that a more distant lens acts as a stronger lens for a far away source, though the image separation also decreases in angular units as $\sim \ell/D_l\sqrt{\Sigma/\Sigma_{\rm cr} - 1}$, where ℓ is a typical scale length of mass distribution in the lens. Spiral galaxies can produce multiple images if located at moderate redshift. For instance, the disk of the milky way has surface mass density of 0.01 gm/cm^2 in our neighbourhood and of the order of 0.1 gm/cm^2 near the centre, which will be close to 1 gm/cm^2 if measured at edge on orientation. Consequently, the disk of our galaxy, viewed edge on, can form multiple images if it is at redshift of $\sim$ 0.1.

Some of the lensing characteristics of spiral galaxies which make it a valuable tool of cosmology are

1. Ellipticity of the projected surface mass density of the lens depends on the orientation of the disk. Thus, certain orientation of the disk of the spiral can produce

eye-catching image configuration which provide strong constraints on the lens models.

2. Spirals are gas rich and readily produce absorption lines which carry signatures of the line of sight rotation curve of the galaxy as well as chemical abundance of various species.
3. Many of the spirals are field galaxies and hence the lensing action is likely to be due to a single object though the lensing by the bulge and disk component have different characteristics. But the angular separation of the images would be small and at least some component of the source would have more than two images. This makes them useful targets for time delay measurements between the images, if the source were variable.

There are three probes to the mass distribution in the lens spiral.

1. Models of the multiple image configuration.
2. Rotation curve inversion from resolved absorption profiles.
3. Baryon mass distribution and its chemical and thermodynamic state through the absorption line strength and width of various lines.

In this talk the methods will be illustrated through an example, though qualitatively.

2. Model analysis

We have carried out detailed observations and modelling of two systems, the Ooty lens 1830−211 [1,2] and 0218+357 [3,4]. In both cases, the two images of a compact flat spectrum radio source as well as a ring like morphology produced by the lens action on extended features of the source provide good contsraints on the lens, from which the orientation of the major axis of the lens as well as approximate inclination of the disk, its scale length of mass distribution and surface mass density can be estimated.

3. Absorption line analysis

A typical absorption profile is shown in the figure 1, observed in the system B0218+357. The main two peaks have widths of approximately 10 km/sec each, thus indicating that they are formed by a small number of clouds having similar rotation velocity. The difference between the two peaks, 26 km/sec is the difference in the line of sight rotation velocity between the two images. It turns out, from the accurate position of the images and modelling of the configuration, that one of the images is close to the lens centre and the other one, within 15 degrees of the minor axis of the spiral galaxy. In addition, the disk is at an inclination of 25 to 35 degrees. The small difference in the rotation velocity between the images is consistent with both these results from the model. The shallow absorption profile, which is significant at 6 sigma level, but worth observing at higher sensitivity, has a doppler width of 160 km/sec. From the radius of the ring responsible for this feature (200 milliarcseconds at redshift of 0.685), we derive that the line of sight rotation velocity is approximately 80 km/sec at 1.5 kpc from the lens centre. Using the eccentricity of

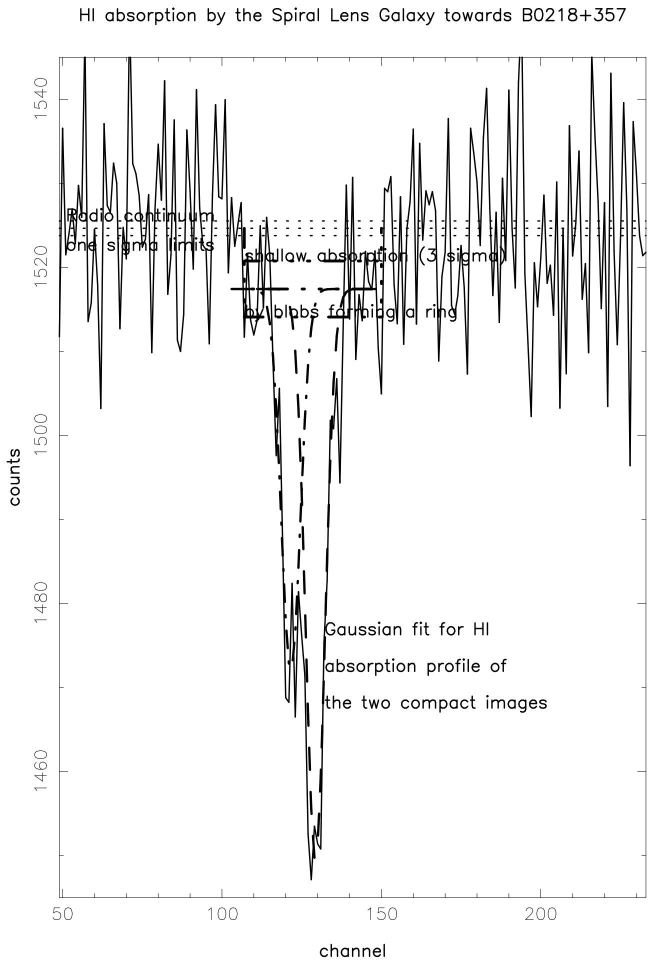

Figure 1. A sample absorption line (solid line) due to a lens spiral galaxy. The source has a compact flat spectrum component of which two images are observed and some steep spectrum blobs, the images of which form a ring like structure. The absorption line is decomposed into two Gaussian profiles due to the compact images (dashed and dash dotted curves) and a shallow component due to the blobs (mean of which is a straight dot dot dash dot line). The difference in the peaks turns out to be approximately 27 km/sec. The shallow absorption component is at least 160 km/sec wide, but it is not smooth because the blobs do not form a continuous ring. The 1 σ limit of the continuum is drawn as dotted lines and 3 σ limits of the mean value of the shallow absorption features are shown as long dash-dotted line. From these limits it is evident that the absorption feature is reliable at better than 6 σ in spite of the noisy nature of the data. The figure is based on an ongoing work with J Chengalur and A G de Bruyn, and the observation was carried out at WSRT, Dwingeloo.

0.45 to 0.55, the expected rotation velocity is in the range of 150 to 200 km/sec. This is a lower limit because the shallow line is curtailed due to noise in the data as well as discontinuity in the ring. If the galaxy is similar to the milky way, the derived rotation velocity is likely to be the asymptotic value; but many of the Sc spirals have increasing velocity even outwards, in which case the value could be higher. In essence, the galaxy has characteristics similar to ours. A similar analysis was carried out for 1830−211 where the line of sight rotation velocity was derived to be 160 to 175 km/sec and the eccentricity of the order of 0.7 to 0.75. Consequently, the rotation velocity was estimated to be 220 to 250 km/sec.

Chemical analysis: The column density of neutral atomic hydrogen can be estimated from the optical depth and line width of the Gaussian fits to the two main components. The derived value is proportional to the spin temperature of hydrogen, which, in both these cases is estimated to be in the range of 300 to 500 K. However, without multiple absorption lines we cannot derive quantitative results on the column density or thermal structure. In the case of 1830–211, the OH doublet has equal intensity. That along with the other numerous lines observed [5,6] indicate that the molecular lines originate from extended regions of diffuse clouds where the radicals are reach thermal equilibrium with radiation rather than by collision between electrons or other species [2].

4. Summary and outlook

Gravitational lensing by spiral galaxies will be an exciting field of cosmology in the coming years. If bulk of these galaxies are isolated, the image separation could be a true indication of the mass distribution at galaxy scales. The chemical and dynamical diagnostic will be reliable due to the rich gas content of the galaxies. The Faraday rotation will provide methods to study the evolution of galactic magnetic field at intermediate redshift and the rotation curve profile will have strong implications on the total mass content of the galaxies.

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