IS IRAS F10214+4724 GRAVITATIONALLY LENSED?

J. LEHÁR
Harvard-Smithsonian Center for Astrophysics

AND

T. BROADHURST
Johns Hopkins University

Abstract. We show that the $z = 2.3$ IRAS source F10214+4724 is gravitationally lensed by an intervening galaxy, as suggested by the observed near-IR structures. Its many anomalous properties can be explained if the source is an ordinary Seyfert 2 nucleus whose central regions are much more highly magnified than the surrounding host galaxy. Confirming expectations, we find a counterimage to the near-IR arc, and find spectral evidence for the lensing galaxy at $z \sim 1$. We present new optical images which show that the optical source is compact and highly magnified. F10214+4724 may represent a population of lensed AGNs whose central engines are obscured.

1. Introduction

The IRAS source FSC 10214+4724 (hereafter F10214) has attracted a great deal of attention in the past few years. It was discovered in a redshift survey of 1400 IRAS sources (Broadhurst et al. 1995), which were selected from the IRAS Faint Source Catalog. At $z = 2.3$, F10214 has by far the largest redshift in the survey (Rowan-Robinson et al. 1991), with an inferred far-IR luminosity of $L \sim 3 \times 10^{13}\, h^{-2}\, L_\odot$, an order of magnitude more luminous than any known source. CO line emission was also detected, also with a very high inferred luminosity (*e.g.* Brown & Vanden Bout 1991). The high inferred far-IR and CO luminosities led many investigators (*e.g.* Rowan-Robinson et al. 1991) to propose that F10214 was undergoing an intense starburst. However, the UV-optical spectral line ratios and the presence of highly polarized spectral emission suggested that the source is an extremely luminous Seyfert 2 nucleus (*e.g.* Lawrence et al. 1993).

C. S. Kochanek and J. N. Hewitt (eds), Astrophysical Applications of Gravitational Lensing, 247–252.

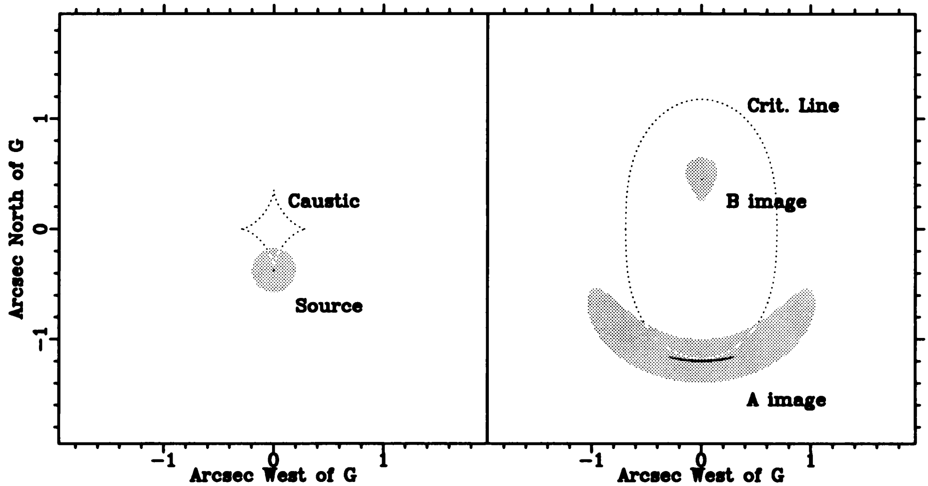

Figure 1. Gravitational lens model for F10214, showing the source (left) and image (right) planes. The lens is centered on G and elongated N-S, with $\beta = 0.91''$, $\epsilon = 0.18$. The source consists of a small region ($r = 0.2''$) which produces the moderately magnified arc ($m \sim 5$), and a compact core ($r = 0.01''$) which is highly magnified ($m \sim 50$). The source is offset by $b = 0.024''$ from a cusp in the caustic.

Here, we propose that F10214 is an ordinary Seyfert 2 nucleus which has been gravitationally lensed by a foreground galaxy. High resolution near-IR images showed four objects near F10214 (Matthews et al. 1994), of which the brightest (Source 1) forms a $\sim 2''$ arc focused on the fainter Source 2, $1.2''$ away. The middle of Source 1 has a $\sim 0.5''$ core which is dominated by $H\alpha$ line emission. Matthews et al. (1994) suggested that the arc was gravitationally lensed by Source 2, but the marked difference between the continuum and $H\alpha$ structures led them to favor a merger scenario. We show that the structural differences at various wavelengths are the key to a complete understanding of F10214's many unusual properties. A more complete discussion of this is presented in Broadhurst & Lehár (1995).

2. Lens Interpretation

We propose that the light from the distant IRAS source is magnified by the gravitational field of an intervening galaxy. We identify the IRAS source with the arc-shaped object (Source 1), and the lensing galaxy "G" with the central object (Source 2). Sources 3 and 4 cannot be additional lensed images of the IRAS source, and presumably these are just other galaxies close to the line of sight.

We designed a simple lens model which can produce the different struc-

https://doi.org/10.1017/S0074180900231422 Published online by Cambridge University Press

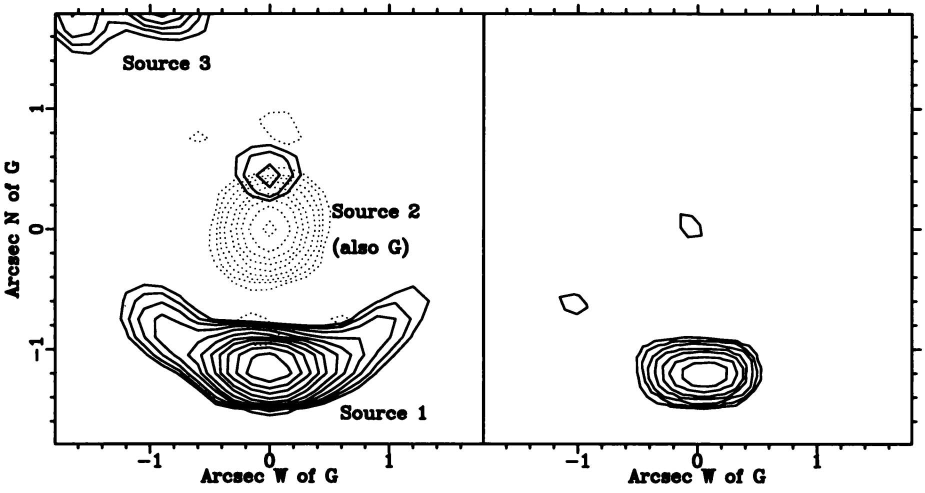

Figure 2. The left panel shows the Near-IR image of F10214 from Matthews et al. (1994) The image was sharpened to 0.3″ resolution, and decomposed into symmetric (dotted contours) and asymmetric (solid contours) parts, by rotating by 180° around the center of G and subtracting. The right panel shows the new optical image, sharpened to 0.2″ resolution. The contours decrease in factors of 1.414 from the map maximum.

tures seen in the near-IR and $H\alpha$ images, and which magnifies the far-IR source enough to make it intrinsically unremarkable. We used a singular isothermal ellipsoidal potential (Blandford & Kochanek 1987), and placed a small source with a compact core just outside a cusp of the astroid caustic (see Figure 1). Two images of this source are formed: an arc-shaped image "A" to the South, and a smaller counterimage "B", just North of the lensing galaxy "G".

A feature of such a lens model is that the magnification m depends strongly on the source angular size r. Basically, small sources will be very highly magnified, while larger sources will be only moderately magnified. Thus in our model, the far-IR source and the $H\alpha$ source are compact objects with $r \sim 0.01''$ and $m \sim 50$, while the near-IR continuum corresponds to a larger source with $r \sim 0.2''$ and $m \sim 5$. The CO and radio emission (Lawrence et al. 1993) would also originate from a smaller source region. Note that unless the far-IR emission is magnified by at least a factor of 20, the source remains intrinsically very luminous, and the fact that it is gravitationally lensed only makes F10214 *doubly unique*.

If F10214 is gravitationally lensed, two simple predictions must be met. First, there should be a counterimage to the arc North of G. We have reanalyzed the near-IR data of Matthews et al. (1994), and find a counterimage $\sim 0.45''$ North of G (see Figure 2). Second, the lensing galaxy must be at a lower redshift than the source. The published spectra of F10214 (*e.g.* Rowan-Robinson et al. 1991) show a distinctive upturn in the continuum flux for $\lambda > 8000$ Å, suggesting a galaxy spectrum at $z \sim 1$.

New optical observations confirm the lensing interpretation, and provide an important constraint to the magnification. We obtained two ten-minute B-filter exposures on the William Herschel Telescope. The images cover the source and two nearby bright stars, and the seeing was $0.6''$. We deconvolved the images using the Lucy-Richardson algorithm, and Figure 2 shows the result of co-adding both images. A single bright arc is visible, coincident with the near-IR "core". Like the radio source, the arc is oriented E-W, with most of its flux toward the Western end. The arc is $\sim 0.5''$ long (FWHM), and its inferred magnification from our model is ~ 50. The arc is unresolved in the N-S direction, setting an upper limit on the source size of $r < 0.5\,h^{-1}$ kpc at $z = 2.3$. The arc's magnitude is $B \approx 21.5$, and no counterimage is detected to a 3σ level of $B \sim 25$. This limits the optical magnification to $m > 20$, which is consistent with the arclength constraint. The lensing galaxy G is also not detected, so it must be very red ($B - K > 7.3$), consistent with an early-type galaxy at $z > 0.5$.

3. Discussion

The near-IR geometry constrains a lens model, which can be used to study the lensing galaxy. Since the arc has a small counterimage and is very symmetric, and since B is closer to G than to A, the mass must be elongated with its major axis within a few degrees of the N-S axis. The positions of A, B, and G constrain the ring radius to $\beta = 0.91''$, and the intrinsic source position to $0.38''$ South of G. The ellipticity ϵ is determined by the requirement that the core of A be highly magnified. The size of the caustic increases with ϵ, reaching the source center when $\epsilon = 0.18$ (or isodensity axial ratio ~ 0.6). The ring radius β provides an estimate of the lensing mass. For a lens at $z_L \sim 1$ and a source at $z_S = 2.3$, the ring size $\beta = 0.91''$ gives an isothermal velocity dispersion of $\approx 320\,\mathrm{km\,s^{-1}}$, or a mass of $\sim 3 \times 10^{11}\,h^{-1}\,M_\odot$ within β. The near-IR magnitude of G converts to a standard magnitude of $B \sim -20.0$, if we assume an early-type galaxy spectrum. This gives a central mass-to-light ratio of ~ 25, and the predicted velocity dispersion is consistent with the Faber-Jackson relation.

The unusual properties of F10214 are all consistent with the background source being an ordinary AGN. The central engine is obscured by a dusty "torus", and perhaps can only be directly detected with sensitive hard X-ray observations. The obscuring torus itself is expected to be $10 - 100$ pc across. If the source is highly magnified, lensing limits the size to $r < 1.8''\,m^{-1}$. Also, a thermally emitting torus at 80 K must satisfy $r > 0.14''\,m^{-0.5}$. For

$m = 50$, this means that $r \sim 0.03'' \sim 100\,h^{-1}\,$pc. Comparing F10214 to the nearby Seyfert 2 NGC1028, the obscuring torus itself would radiate predominantly in the IR, with an IR luminosity of $L_{IR} \sim 5 \times 10^{11}\,L_{\odot}$. The apparent far-IR luminosity of F10214 could easily be achieved if the torus were magnified by $m \sim 50$. The optical/IR spectrum is Seyfert 2 like, and is polarized by $\approx 15\%$ (*e.g.* Lawrence et al. 1993). Such high levels of polarization are found in the "mirror" regions of local Seyfert galaxies, which are generally $50 - 100\,$pc across. Sources of this size could produce the $\sim 0.5''$ optical arc if $m \sim 50$, so we suggest that this arc is a highly magnified image of such a mirror. The outer regions of the host galaxy would be less highly magnified. The $2''$ near-IR arc could be produced in the bulge of the host galaxy, with $r \sim 0.2'' \sim 1\,h^{-1}\,$kpc. The outer galaxy should produce faint ring-like optical structures at $1'' - 2''$ radii.

The view that F10214 is a lensed AGN solves several other problems associated with this source. This source is very "red" in the IR, in that its apparent far-IR to near-IR flux ratio is much higher than for local Seyfert 2 nuclei (Lawrence et al. 1994). This is easily explained if the core is preferentially magnified. If the AGN narrow line region has any ionization structure, the spectral lines will be magnified by different amounts. This may explain the anomalously large high ionization lines, like NV in F10214, compared to other Seyfert 2s. High magnification can explain the unusually bright CO emission. The high temperature deduced from the CO transitions (Solomon et al. 1992) and the observed velocity profile are consistent with conditions in AGN centers. The unexpected polarization angle is also explained. The **E** vector of polarized optical emission is usually perpendicular to the radio elongation in Seyfert 2 sources. In F10214, the polarization shows no special alignment with the radio structure (Lawrence et al. 1993). In our model, the radio source is stretched by a factor of > 20 by lensing, so the observed elongation is unrelated to any intrinsic structure.

The *a priori* probability of finding systems like F10214 in the IR redshift surveys is encouragingly large. The IRAS redshift survey in which F10214 was found covers $0.2\,$sr down to $0.2\,$Jy at $60\,\mu$, and the redshifts extend over $z < 0.4$. Two evolution models can be fit to the source counts: pure luminosity $\propto (1+z)^5$; and pure density $\propto (1+z)^{2.5}$. We have calculated the total cross-section to lensing, accounting for the high magnification bias from elliptical lenses (Wallington & Narayan 1993). Applying both evolution models, $0.3 - 1.2$ lensed systems are expected, and it is not improbable that lensed systems should have been discovered in this survey. The calculation also gives expectation values for the lens redshift $< z_L > \sim 0.7$, the source redshift $< z_S > = 1.2 - 2.0$, and the source magnification $< m > = 25 - 40$.

4. Concluding Remarks

We have seen that many of its unusual properties can be readily explained if F10214 is a gravitationally lensed Seyfert 2 nucleus. Obscured AGNs could be more useful than QSOs for probing the lens galaxy mass distributions, since their background emission is measurably extended. Many more such systems should be found, and the IRAS source F15307+3252, at $z = 0.93$ (Cutri et al. 1994), is probably another case like F10214. The lensed QSO H1413+117 ($z_S = 2.5$) is a strong CO emitter (Barvainis et al. 1994), and may be a face-on version of F10214. Current searches for lensing have used optical QSOs and active radio sources, which are only a subset of the full AGN population. Selection by far-IR allows a fuller coverage of AGNs but is presently limited by the relatively bright IRAS flux limit.

There is more work to be done on F10214 itself. The counterimage has been confirmed in a recent Keck Telescope image (Graham & Liu 1995), and in new HST observations (Eisenhardt et al. 1995). The HST images also show that the main arc has substructures. Multicolor HST observations could determine whether these are multiple images of a single source or several separate source components. The latter would be very exciting, since those structures could never have been resolved without the aid of gravitational lensing. The most important unresolved issue remaining is the lens redshift. Our initial estimate of $z \sim 1$ is supported by the $z = 0.8$ result of Serjeant et al. (1995), based on similar features. However, Goodrich et al. (1995) identify absorption lines at $z = 1.2$. There have also been reports of $z \sim 0.4$ measurements (Close et al. 1995). Until this issue is settled, the lens mass estimates will be imprecise. For $0.8 < z < 1.2$, the required lensing mass varies by 30%.

References

Barvainis R. et al., 1994, Nature, 371, 586
Blandford R. & Kochanek C., 1987, ApJ, 321, 658
Broadhurst T. & Lehár J., 1995, ApJ, 450, L41
Broadhurst T. et al., 1995, ApJ, in preparation
Brown R. & Vanden Bout P., 1991, AJ, 102, 1956
Close L.M. et al., 1994, to appear ApJL (Oct 10)
Cutri R. et al., 1994, ApJ, 424, L65
Eisenhardt P. et al., 1995, to appear in ApJ
Goodrich R. et al., 1995, in preparation
Graham J. & Liu M., 1995, ApJ, 449, L29
Lawrence A. et al., 1993, MNRAS, 260, 28
Lawrence A. et al., 1994, MNRAS, 266, 41P
Matthews K. et al., 1994, ApJ, 420, L13
Rowan-Robinson M. et al., 1991, Nature, 351, 719
Serjeant S. et al., 1995, to appear in MNRAS
Solomon P. et al., 1992, ApJ, 398, L29
Wallington S. & Narayan R., 1993, ApJ, 403, 517