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Further observational evidence that MG J0414+0534 is a gravitational mirage*

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Abstract. Deep imaging of MG J0414+0534 with R and I filters reveals a faint, fuzzy and red object at the exact location expected for a lensing galaxy in the gravitational mirage hypothesis. Furthermore, the (extremely red and almost featureless) spectra of the 2 brightest components are very similar.

These are strong indications that the system results from multiple gravitational imaging of a single source, but the nature of this source is not yet clear. It could be the nucleus of a low metallicity galaxy at a high redshift or a new type of object.

Significant differences are observed between the flux ratios of the images at radio and optical wavelengths. The most likely explanation for this effect is a differential amplification of the image pair A_1-A_2 because of the large magnification gradient near a caustic.

Key words: gravitational lensing – radio sources – MG J0414+0534

1. Introduction

Among the various effects of gravitational lensing, the gravitational mirage phenomenon (i.e.: multiple imaging of a distant source) is a rare but especially interesting occurence. Seeing a single object through different pathways may have several astrophysical applications. Of the very few cases discovered until now, almost each one is singular and MG J0414+0534 (although is has been omitted until now, we add the prefix J because the coordinates are expressed for equinox 2000) is a candidate with puzzling characteristics.

The peculiar morphology of this source was recognized during a search for gravitational mirages candidates in the MIT-Green Bank Survey (Bennett et al. 1986). High resolution VLA maps showed 4 unresolved images with similar radio indices between 5 and 15 GHz, in a configuration closely ressembling that of the radio-quiet PG 1115+080 (Hewitt et al. 1988a). At optical wavelengths, faint images are seen at the locations of the radio components, with approximately the same intensity ratios. This constitutes a good evidence for a gravitational lensing system, without being a definite proof; in particular, no lensing body was detected until recently (Schechter & Moore, 1993; hereafter SM) and the nature of the source is still unknown (Hewitt et al. 1992; herafter HTLSB).

The new observational results on MG J0414+0534 presented in this article throw some light on these two issues and reinforce the gravitational lens interpretation.

2. Observations

The observations were made at ESO (in the framework of a Key-Programme on gravitational lensing) and at CFHT. A set of CCD pictures has been obtained in good seeing conditions and with a fair sampling; the spectroscopy of the 2 brightest components was also attempted with the spectrograph EMMI on the NTT. The best data, which we will analyse here, are listed in Table 1.

2.1. Imagery

The data from CFHT were obtained with the imaging mode of the spectrograph SILFID (Vanderriest & Lemonnier 1988). In this configuration, the transmission of the optics is around 0.7 - 0.8 for the considered wavelength range. The same is true for the data obtained with EFOSC2 on the NTT.

2.1.1. Analysis of the optical structure; detection of the lensing galaxy

On all the individual frames in I band and on the best frames in R, a fuzzy component is already visible, very near the expected position for a lensing galaxy (see for instance the model in HTLSB).

We generated a composite picture in I by summation of the CFHT and the NTT exposures, after reduction to a common

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* Based on observations collected with the Canada-France-Hawaii Telescope at Mauna Kea (Hawaii, USA) and with the NTT of the European Southern Observatory (Chile)

Table 1. Journal of observations

Date (y-m-d)	telescope + instrument	filter or grism	exposure time (mn)	seeing or slit width ($''$)	sampling ($''$/pixel)
91-12-07	CFHT + SILFID	V	20	1.0$''$	0.21$''$
91-12-08	CFHT + SILFID	V	2×15	0.85$''$	0.21$''$
91-12-09	CFHT + SILFID	V	30	0.9$''$	0.21$''$
90-08-24	NTT + EFOSC2	R	30	0.65$''$	0.15$''$
91-12-07	CFHT + SILFID	R	2×15	0.8$''$	0.21$''$
91-12-08	CFHT + SILFID	R	15	0.85$''$	0.21$''$
92-09-21	2.2m ESO + CCD	R	2×30	0.85$''$	0.18$''$
92-09-25	NTT + SUSI	R	20	0.75$''$	0.13$''$
92-03-01	CFHT + SILFID	I	2×10	0.6$''$	0.18$''$
92-09-25	NTT + SUSI	I	15	0.7$''$	0.13$''$
92-01-11	NTT + EMMI	G1	45	2$''$	0.46$''$
92-01-12	NTT + EMMI	G4	45+30	2$''$	0.46$''$
92-09-26	NTT + EMMI	G4	2×40	1$''$	0.46$''$

sampling of 0.13$''$ by a spline interpolation. The final picture, slightly smoothed (gaussian filter with FWHM = 1 pixel) has a resolution around 0.73$''$ and shows very conspicuously the fuzzy component (Fig. 1a) suspected on individual frames. The images B and C are not resolved, while the elongation of image A can be reproduced by a model of 2 point sources (A_1 and A_2) with an intensity ratio $\simeq$ 2-3 and separated by around 0.45$''$. This configuration is in good agreement with the radio maps from the VLA (Katz & Hewitt 1993), except for the A_1/A_2 ratio . In order to measure the extended ("galaxy") component, we thus have to subtract 4 point sources with proper locations and amplitudes.

We firstly used an automatic decomposition algorithm with synthetic bidimensional PSF, especially written for the processing of such complex images (Magain et al. 1993). It works extremely well when the PSF is invariant in the field, which is not strictly realized in this case. The best fit corresponds to A/B = 3.2 and B/C $\simeq$ 2.0 and gives very small residuals in the outer parts of the complex image, thus confirming that the source is not resolved. As there is no real overlap between A (taken globally), B and C, we could also attempt a direct decomposition by interactive gaussian fitting in X and Y. This method gives also a good result, with A/B = 3.2 and B/C $\simeq$ 3.0. The profile of the left-over "galaxy" looks even smoother in the region of image C (Fig. 1b). In fact, the decomposition depends on the assumed profile of this galaxy. The difference for the amplitude of the faintest image between the 2 methods is thus not too surprising. A closer examination of the raw data suggests that the real value for B/C is somewhere between the above values; we adopt B/C = 2.5 ± 0.5. The galaxy G is definitely extended, with FWHM $\simeq$ 1.5$''$.

A combination of our best R pictures (Fig. 2a), giving a final resolution of 0.87$''$, shows also clearly the galaxy G and was processed in the same way as the I picture, producing the residual displayed on fig 2b. The relative importances of the different components is very similar to those of the I picture.

On the composite V picture (Fig. 3a), MG J0414+0534 is hardly detectable. The position of the most conspicuous feature indicates that it results from a mixing of G and A; the isophotes of G (average of R and I data) are superimposed on Fig. 3b for comparison. The image B is just emerging from the noise, while C is below the detection threshold.

2.1.2. Photometry

The flux calibration of the different frames relies on observations of a few standard stars from Landolt (1983) or a sequence in NGC 2264 (Christian et al. 1985). The agreement between these independent calibrations is very good, indicating a zero point error probably less than 0.05 mag. The resulting magnitudes are listed in Table 2 for the source images and the galaxy G, as well as for a few reference stars and 3 typical galaxies in the field (identification in Fig. 3). The flux ratios of the images are given in Table 3 and compared to other measurements; their relative positions are in Table 4. The measured flux of galaxy G is in good agreement with SM in I filter; for the R filter, it is much larger (by 2 magnitudes) than the upper limit given by HTLSB. The most likely explanation of this discrepancy is that galaxy G is not well resolved in their data because of the poorer seeing and S/N. As a consequence, the flux of the faintest image (C), which is also the closest to G, was largely overestimated.

The colour indices of the different objects in the field can be obtained from Table 2. The putative deflecting galaxy is very red (redder than galaxies g_1 to g_3) but not as much as the radio source itself. We notice the similar colours of the 3 images, near 1.8 in (R-I) and no contradiction of our data with the hypothesis of similar colours in (V-R).

Finally, we added together the composite I and R pictures, in order to reach a deep detection level on red objects. On this frame (fig 4) we notice the presence of some very faint galaxies in the field (the R magnitude of the faintest objects detected is around 26.5) without obvious clustering around the mirage.

Table 2. Photometric data

Object :	V	R	I	(R-I)
M	22.67 ± 0.08	21.09 ± 0.04	19.23 ± 0.04	1.95 ± 0.1
2	22.59 ± 0.08	21.41 ± 0.04	20.21 ± 0.05	1.2 ± 0.1
3	22.61 ± 0.08	21.98 ± 0.05	21.09 ± 0.06	0.9 ± 0.1
4	23.80 ± 0.15	23.04 ± 0.07	21.92 ± 0.08	1.1 ± 0.1
5	> 25	24.03 ± 0.10	22.07 ± 0.10	1.95 ± 0.15
6	24.7 ± 0.4	23.70 ± 0.10	22.09 ± 0.10	1.6 ± 0.15
g_1	24.3 ± 0.3	23.8 ± 0.15	22.9 ± 0.15	0.9 ± 0.2
g_2	23.6 ± 0.2	23.0 ± 0.10	22.2 ± 0.12	0.8 ± 0.15
g_3	23.0 ± 0.15	22.4 ± 0.08	21.55 ± 0.10	0.85 ± 0.15
G	24.4 ± 0.5	22.4 ± 0.15	20.85 ± 0.10	1.55 ± 0.2
A	24.7 ± 0.5	22.15 ± 0.08	20.33 ± 0.06	1.8 ± 0.1
B	25.5 ?	23.35 ± 0.12	21.61 ± 0.10	1.7 ± 0.2
C	> 25.5	24.6 ± 0.2	22.6 ± 0.2	2.0 ± 0.3
"X"	> 25.5	26.3 ± 0.5	24.7 ± 0.5	1.6 ± 0.7

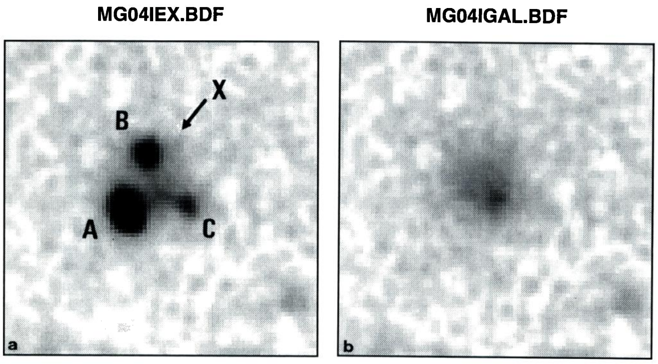

Fig. 1a and b. Composite picture of MG J0414+0534 in I band (see text). The field is 10″ on a side. Galaxy g_1 is on the lower right corner. **a** raw picture **b** residuals after subtraction of the images A, B and C

A very faint component is seen near the position of the "object X" detected by SM. On both the R and I composite pictures, it is close to the 3 σ magnitude limit, but still measurable. The (R-I) colour index is too poorly determined to be really useful. It is compatible with X being another image of the source, but a more likely interpretation is that it is a distant galactic star unrelated to the lens system.

The R data, independently reduced for the 3 epochs of observation (August 90, December 91 and September 92), do not show clear evidence for a variability of the source: the total amplitude found for image A, $\Delta R = 0.20 \pm 0.12$, could not be considered significant. Moreover, the global flux (A+B+C+G) is comparable to the previous measurements (HTLSB) in 1987 and 1989. Let us also notice that we should be cautious when comparing different observations of this objet: because of the steepness of its spectrum, the photometry is very sensitive to the exact shape of the instrumental passband, which includes filter, CCD response curve and atmospheric extinction. For instance, this explains the notable difference between our photometric data in I band and the I' data from SM.

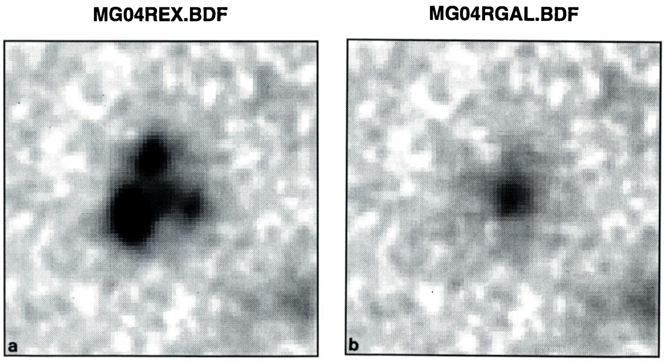

Fig. 2. Composite picture of MG J0414+0534 in R band (same processing than for Fig. 1)

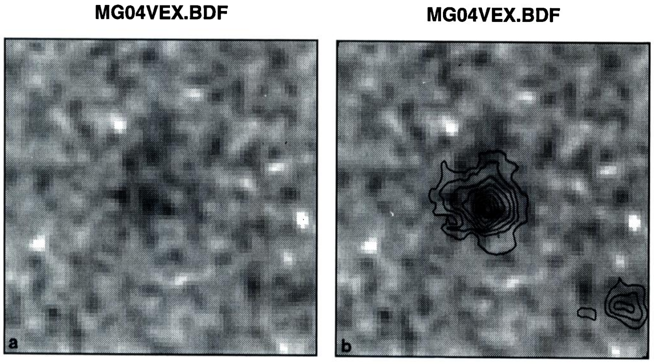

Fig. 3a and b. Composite picture of MG J0414+0534 in V band. **a** raw picture **b** Superimposed to the same picture, an isophotal plot of the galaxy, from the average of the I and R data

2.2. *Spectroscopy*

For the observations with EMMI, the slit was positioned along the A-B direction. The seeing was around 0.8″ in all cases, allowing a good separation of the 2 spectra (Fig. 5, insert). In January 1992, the 2″ slit width gave resolutions around 20 Å and 45 Å, respectively, for the 2 used grims. For the September data, the slit width was 1.0″, giving a resolution of 10 Å. The spectrophotometric standard was H 600 (Massey et al. 1988; Massey & Gronwall 1990).

Figure 5 shows the sum of all the exposures with grism G4, reduced to the lowest resolution and slightly smoothed (final resolution 30 Å). The 2 spectra have a very similar shape, with a constant flux ratio (around 3) in the whole wavelength range. As already known for the sum A+B, the continuum is very red and without obvious feature, except for a deep absorption line near 8663 Å (HTLSB). This line, seen on both spectra, does not seem to be an artefact from night sky subtraction. A sky emission band from O_2 is close to the measured wavelength and quite strong, but not as strong as the surrounding OH(6,2) and (7,3) emission complexes. Beyond 9250 Å, the spectrum is plagued by atmospheric absorption and poor Signal/Noise; nothing reliable could be measured.

The 8663 Å absorption is the only secure feature. We observe also a slight raising of the continuum redwards of this

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Table 3. Flux ratios

Ratio:	radio 1987 (HTLSB)	I 1987 (HTLSB)	I 1991 (SM)	I 1992 (this work)
A/B	5.0 ± 0.2	2.9 ± 0.1	3.2 ± 0.2	3.2 ± 0.2
A/C	14 ± 1	(4.3 ± 0.2)	7.3 ± 0.5	8 ± 1
B/C	2.8 ± 0.2	(1.5)	2.3 ± 0.3	2.5 ± 0.5

line, already noticed in HTLSB but attributed to residuals of sky subtraction. The feature could be real, since we can trace it between 8670 and 8760 Å, a region almost free of sky emission on the best resolution data. A priori, this would suggest an identification with the 4000 Å break, the 8663 Å absorption being then identified with Ca H + Hϵ, which gives the tentative redshift $Z_S = 1.18$.

Another value $Z_S = 2.63$ has been mentioned for this object (for instance in a review paper by Blandford & Narayan 1992) but the data are not yet published. This value is neither strongly supported nor excluded by our spectra: nothing is detected at the expected position of Ly α from the data with the grism G1, which cover the interval 4000-10200 Å. It would imply a very large reddening in the source itself. The 8663 Å absorption feature could be interpreted as the 2380 FeII blend observed in the spectra of star-forming galaxies (Kinney et al. 1993); it could also be a feature related to the lensing galaxy or a foreground object. So, in the following, we will consider that the redshift of the source is *at least* 1.18; the conclusions about the lensing are essentially the same for a higher value.

3. Discussion

3.1. The nature of the source

The extremely red colour of MG J0414+0534 could result, in part, from strong absorption by dust and reddening. In this area, the instellar absorption is negligible (Burstein & Heiles 1982), corresponding to E(B-V) < 0.2. A reddening by the lens galaxy G is unlikely: in order to explain the observed colours, such a reddening should be exactly the same for image A and B (and, with a lesser precision, C) while these images are seen through different parts of G. This would mean a surprisingly uniform absorption on a scale of 10 kpc. Thus, if a large reddening is involved, it is more likely intrinsic to the source.

We do not understand exactly the nature of this source, but could find similarities with two other lensed objects which have also a very red spectrum and a strong radio flux. The "Einstein ring" MG J1131+0456 (Hewitt et al. 1988b; Hammer et al. 1991) is bright in infrared and is described as an "unusually red radiogalaxy" (Annis 1992). The ring 0218+357 (O'Deal et al. 1992; Patnaik et al. 1993) is very red too and its optical spectrum, with an almost vanishing 4000 Å break, bears some ressemblance with the one of MG J0414+0534.

Indeed, MG J0414+0534 and MG J1131+0456 are among the reddest extragalactic objects, with R-K indices larger than 6. The latter one can be classified as a radiogalaxy because of its optical extension (Hammer et al. 1991), while the compactness of MG J0414+0534 (size smaller than 5 kpc for $Z_S > 1$ and $H_o = 50$) makes it more similar to the infrared objects that Walsh et al. (1985) classified as QSOs. It could be, also, the bright nucleus of a faint radiogalaxy. Anyway, despite their large radio fluxes, MG J0414+0534 and MG J1131+0456 are not classical radiogalaxies; neither could they be assimilated to classical BL Lac. objects. Taking into account the magnification by lensing (cf. Hammer et al. 1991), their infrared luminosities are comparable to the ones of 3C galaxies (Annis & Luppino 1993), but they are about 3 magnitudes fainter in visible light (UV at rest) and radio. Another striking difference is the absence of any emission line activity linked with starbust or active nucleus. We thus guess that, aside from the classical powerful radiogalaxies, a new and relatively abundant population of fainter radiogalaxies should exist at high redshifts, with a quite different stellar content. The knowledge of the properties of such objects and their evolution could be important for understanding the galaxy formation process.

Table 4. Relative astrometry (origin on B)

	radio (HTLSB)		optical (this work)	
	$\Delta\alpha$ ($''$)	$\Delta\delta$ ($''$)	$\Delta\alpha$ ($''$)	$\Delta\delta$ ($''$)
A	+0.66 ± .01	− 1.72 ± .01	+0.61 ± .03	− 1.77 ± .03
C	−1.34 ± .01	− 1.64 ± .01	−1.39 ± .04	− 1.56 ± .04
G	−0.38 ± .01	− 1.24 ± .01	−0.45 ± .06	− 1.27 ± .04
	(calculated position for G)			

3.2. The nature of the lens

We do not know the redhift Z_G of the lens galaxy, but its apparent magnitude and size (1.5$''$ FWHM) suggest a value around 0.7-0.8 and the colour indices agree with an elliptical in this range.

The $(M/L)_V$ ratio for Z_G=0.7 and Z_S=1.2 is of the order of 50 if we assume, for the sake of simplicity, a mass distribution corresponding to a singular isothermal sphere or a point mass and the K_V correction of a normal elliptical galaxy. This rough estimate only suggests that the contribution to the lensing by a cluster and/or a dark matter component is not dominant.

For a realistic model, the most needed data now seem to be the reshifts of the source and of the lensing galaxy G. Measuring also the redshifts of the less feeble galaxies in the field (at least, g_2 and g_3) would help to probe the existence of an associated cluster.

3.3. MG J0414+0534 as a gravitational mirage

Even if we do not know precisely the nature of the source and its distance, there is no doubt that it is a remote extragalactic object. The similarity between the two images spectra, the component configuration and especially the detection of a fuzzy object at the "right" place are cumulative evidences for a scenario of gravitational lensing by a medium distance galaxy.

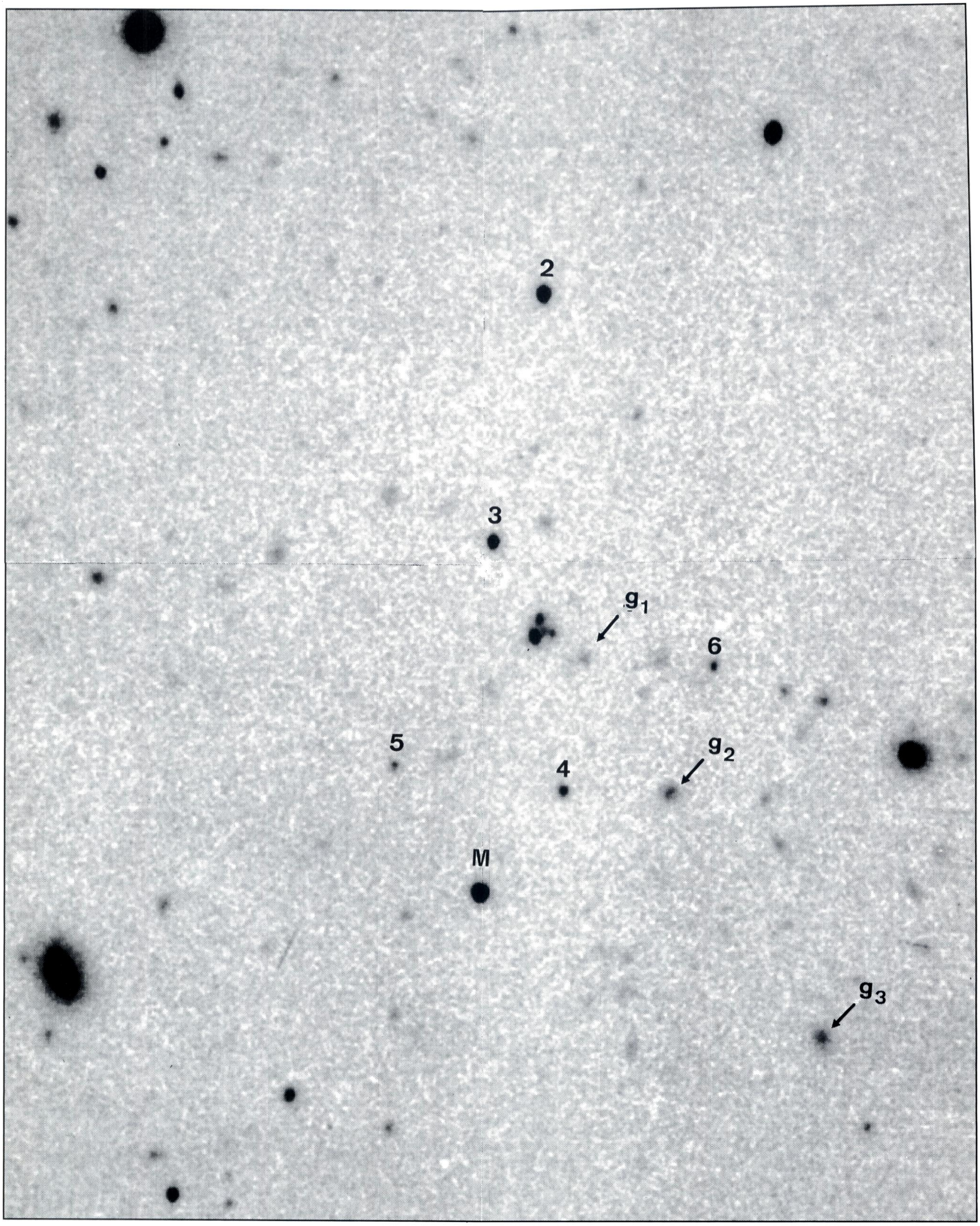

Fig. 4. Sum of all the I and R exposures, with identification of the photometric sequence (field ≃ 1′45″×2′ 10″). Note that most of the faint galaxies are elongated and that g_2 and g_3 show resolved structures

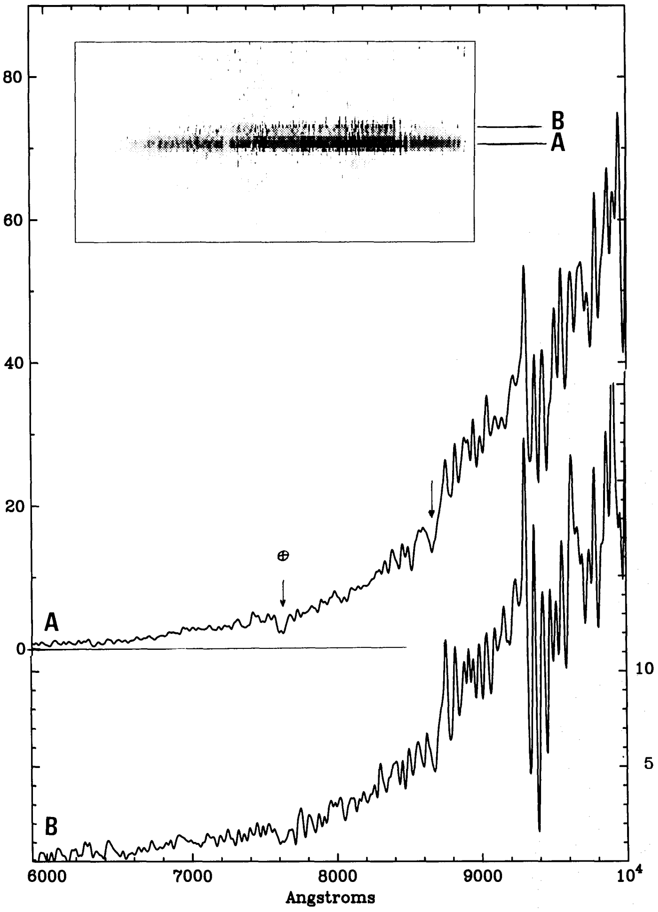

Fig. 5. Spectra of images A and B from the data with grism 4. The fluxes are in units of 10^{-21} W m^{-2} Å^{-1} (left scale for A, right scale for B). The strongest telluric absorptions are identified. Inserted is a bidimensional representation of the coadded data, after removal of cosmetic defects and of the night sky emission

But the flux ratios of the images (Table 3) do not seem to support, at first sight, such a conclusion. The radio data presented in HTLSB correspond to very similar flux ratios at both frequencies of 5 GHz and 15 GHz: 5.0±0.2 for A/B and 14±1 for A/C (thus B/C = 2.8±0.2). On the other hand, our optical data from 1991-92 give A/B = 3.2±0.2, A/C=8±1 (i.e. B/C = 2.5±0.5) in I and A/B=3.0±0.3, A/C=9.5±1.5 (i.e. B/C=3.2±0.5) in R. Our new photometric decomposition is in better agreement with the radio data than the one published in HTLSB; however there remains a significant discrepancy for the A/B ratio, which is rather well measured. This does not mean that the lensing hypothesis must be rejected. Firstly, within the precision of measurements, the radio and optical B/C ratios are identical and everything would be "in order" if the A component were dimmed by a factor 1.6 between the two domains of wavelengths. We can think of several explanations:

(1) *Extinction by galaxy G*: On the high resolution VLA maps published by Katz & Hewitt (1993) the flux ratio A1/A2 is measured at 1.15 ± 0.05 while we estimate it near 0.3 ± 0.1 from the best I pictures. Most of the optical/radio discrepancy is then due to component A1. If obscuration by a cloud in the lensing galaxy is the explanation, it amounts to about 1.5 magnitude in I, which means more than 2 magnitudes in R. We should thus have in this colour A1/A2 = 0.18 and A/B = 2.9. Clearly, this explanation could not be ruled out by the present data. More precise photometry on A1/A2 is needed. However, as G seems to be an elliptical galaxy, such an heavy obscuration seems unlikely.

(2) *Intrinsic variability of the source and time delay effect*: This explanation is also unlikely. There is no well defined variability (cf. Sect. 2.1.2). There is also a significant discrepancy between the radio and optical data obtained almost simultaneously in 1987 by HTLSB. Although their flux measurements of component C are questionable because of the presence of G, the A/B ratio seems secure.

(3) *Variability of image A by microlensing*: Again, there is no direct evidence for a variability with the required amplitude of $\simeq 0.5$ magnitude.

(4) *Differential magnification by microlensing*: This is a well known effect if the positions and/or sizes of the optical and radio sources are slightly different on a scale comparable to the Einstein radius of the microlens. This can also produce a differential magnification between emission lines and optical continuum of a quasar, an effect observed in Q0957+561 (Vanderriest 1990; Schild & Smith 1991) and H1413+117 (Angonin et al. 1990).

(5) *Magnification gradient near a caustic*: There is no real need for a microlensing event. What is needed is a magnification gradient on angular scales comparable to the characteristic size of the source. In the most likely gravitational lensing models of MG J0414+0534, the source would be at a distance $< 0.1''$ from the tangential (inner) caustic and thus already in a region of large magnification gradient.

This effect is invoked in the case of 0957+561 for explaining the different flux ratios observed at radio and optical wavelengths (Conner et al. 1992). It is certainly present here if the source is resolved in radio on a scale of a few $10^{-2''}$ (HTLSB). The radio flux is large enough for VLBI observ ations, which makes it possible to check this interpretation. If a resolved structure is found, like for 0957+561 (Gorenstein et al. 1988) and 2016+112 (Heflin et al. 1991), the magnification variations could be mapped quite precisely.

4. Conclusions and suggestions

We think that MG J0414+0534 is another example of gravitationally lensed source with unusual characteristics: strong radio emission, extremely red and almost featureless optical spectrum. To some degree, it shares these properties with the "Einstein rings" MG J1131+0456 and 0218+357. It is extremely unlikely that such unusual sources have been lensed by chance if they were rare. The best hypothesis is that they belong to a new category of quite common objects which were not previously noticed (maybe because they are abundant only at high redshifts and optically faint when not magnified by the gravitation). In this case, numerous unlensed representants should be found in the MG catalogue, for instance. It would be interesting to undertake a small photometric and spectroscopic survey among the MG sources that are not (or hardly) resolved with the VLA and have no optical counterpart at the limit of the POSS.

More generally, an interesting property of gravitational mirages is to reveal populations that would stay otherwise unnoticed. As it occurs at random, the magnification lessens the observational biases, while multiple imaging is an efficient "flag" for drawing attention to the imaged source. Without magnification, MG J0414+0534 would be fainter than R = 24 and nobody would have taken the trouble to make a spectrum.

Aside from the still unknown nature of its source, this gravitational mirage could be an interesting candidate for astrophysical applications like the measurement of H_o. Even more for this system than for PG 1115+080 (because of the supplementary advantage of being a radio-source), the observations could constraint strongly the models. MG J0414+0534 is the brightest gravitational mirage in radio and shows a simple structure at the resolution of the VLA, unlike H 1413+117 for instance (Kayser et al. 1990). A VLBI study of the 4 images could thus be very informative. Because of the optical faintness of the source, its seems also easier to determine the time delays between the images from radio observations. The lens does not seem to be as complex as the one of 0957+561, but it is not possible to exclude that faint galaxies associated to G are involved in the lensing. Deeper imaging is needed to check this point.

Then, remains the problem of measuring the redshifts of the source and of the lens. The tentative redshift for the source could be confirmed with better S/N optical spectra, which is essentially a matter of integration time with large telescopes. Near IR spectra could also be useful for the determination of Z_S and would give at the same time the shape of the continuum beyond 1 μm. For measuring the redshift of the lens Z_G, bidimensional spectroscopy techniques (e.g. Vanderriest & Angonin 1992) seem required, associated with very powerful light collectors, like the 8-10 m telescopes that will be soon available.

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