Astron. Astrophys. 318, 997–1002 (1997)

ASTRONOMY AND ASTROPHYSICS

Accurate optical-to-radio registration of Seyfert galaxies with HST images

Absolute astrometry of HST images*

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Received 8 March 1996 / Accepted 21 May 1996

Abstract. We propose a method to obtain accurate absolute astrometry of Hubble Space Telescope images. Ground based images are used to link HST images to standard astrometric stars defining the optical frame of reference. The method has been used to register optical images of the Seyfert 2 galaxy NGC 5929 to the corresponding radio maps, allowing the exploration of the relationship between radio and optical emission within the galaxy.

The total uncertainty in the absolute astrometry of one HST image is ~ 62 mas, an order of magnitude better than it is usually achieved with the Guide Star Catalog 1.1 positions, and the final registration with the radio images is derived to *better* than $0.''1$.

The radio core of NGC 5929 falls within a nuclear dust lane. No optical counterpart to the radio nucleus is seen, in agreement with the Unified Model for Seyfert galaxies. The strong association between radio and line emission in this object is confirmed by this work.

There are several different contributions to the final accuracy of the optical-to-radio registration: measuring errors, errors in the absolute radio and optical positions, *local* systematic deviations in the optical-to-radio alignment of the fundamental frame, etc. A significant decrease of the astrometric error budget has to wait for substantial improvements as, for example, those expected from the radio-optical link in the forthcoming Hipparcos Catalog.

Key words: astrometry – galaxies: individual: NGC 5929 – galaxies: Seyfert – methods: data analysis

1. Introduction

With the launch of HST and the use of VLA and MERLIN radio observations, both optical and radio images with a resolution better than $\sim 0.''1$ are routinely available. However, the poor accuracy in the registration of these images prevents taking advantage of such increased resolution to a better understanding of the relationship between radio and optical emission, which is of great interest in several fields of extragalactic astrophysics, and in particular for Seyfert and radio galaxies. The absolute astrometry of HST images is limited by the uncertainties of the Guide Star Catalog positions to, typically, $0.''5$ in the Northern hemisphere (Taff et al. 1990).

In this paper, we propose a method to improve the absolute astrometry of HST images using ground based images to link to astrometric standard stars. The resulting astrometry is of high accuracy and it can be used to define a common reference frame to which both HST and the radio images are referred. This method is applied here for the first time to the Seyfert 2 galaxy NGC 5929, for which both HST and MERLIN images are available.

The observations used for this test are described in Sect. 2. In Sect. 3 we derive the absolute astrometry of the ground based images. Section 4 outlines the method to register ground based and HST images, while Sect. 5 addresses the issue of systematic deviations between radio and optical frames. In Sect. 6, we register the HST and radio images and briefly discuss the results. A summary and our conclusions are given in the last section.

2. Observations

The HST archival images of NGC 5929 (see Bower et al., 1994) were obtained on September 27, 1992, using the WF/PC-I in the PC mode, with a pixel size of 0.043 arcsec. The four 800 x 800 pixels CCD cover a field of view of $66''$ x $66''$. Two images obtained with the filters F664N and F718M were used, the first

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* Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555 and by STScI grant GO-3594.01-91A.

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*** On assignment from the Space Science Department of ESA including the emission from the $H\alpha$ and [N II] lines, the second covering the spectral region 6700 Å– 7600 Å. The exposure times were 1800 and 900 sec respectively. These images were deconvolved using 50 iterations of Lucy's (1974) iterative algorithm and two model Point Spread Functions built with the Tiny Tim software (Krist, 1992) centered respectively on NGC 5929 and its companion NGC 5930, which is located 27$''$ NW of NGC 5929. The continuum emission was then removed from the on-band filter F664N by properly scaling the F718M image.

The star density of the fundamental catalogs presently available is generally too low for the direct calibration of the relatively small fields covered with CCDs. Therefore, two different kinds of ground based images were necessary. Two plates centered on NGC5929 were taken with the 38cm photographic refractor (scale $\simeq$ 30"/mm, field-of-view= 1.°5 $\times$ 1.°5) of Torino Observatory (Table 1). The relatively large FOV of the refractor ensures that a sufficient number of astrometric reference stars is available for the tie to the optical reference frame (see next section). However, direct astrometry of NGC5929 on those plates would not be adequate, as exposure time was optimized for measuring with comparable accuracy both the bright primary and the fainter secondary reference stars. Astrometry of the Seyfert galaxy was done on frames taken in the Summer of 1994 with the EEV 1242 $\times$ 1152 pixel CCD (scale $\simeq$ 0."455/pixel) attached at the f/10 105cm astrometric reflector of Torino Observatory (Table 1). The 600-sec image was selected for the final registration with the HST WF/PC-I R-band image. The FWHM seeing was 1."5, which is average for the Pino Torinese site.

The two photographic plates were digitized with one of the two PDS-type measuring machines available at ST ScI (Lasker et al. 1990). Scanning utilized the raster-type sampling with pixels of 15 μm on a side ($\simeq$ 0."45/pixel). The metrological and stability properties of the digitizer are quite adequate for accurate astrometry, as discussed in Lattanzi et al. (1991). This article also discusses the image centering technique used to measure both the digital copies of the plates and the CCD frames. The centering precision is of the order of, or better than (depending on Signal-to-Noise of each individual image), 1/15 pixel for the photgraphic images, and $\sim$ 1/50 pixel for the CCD images.

HST and ground based images are shown in Fig. 1. The WF/PC-I R band image of NGC 5929 shows a bright central component located immediately North West of a dust lane which crosses its nuclear region along PA $\sim 35^o$. A marginal contamination of line emission in this image produces a knot SW of the peak of emission. The line emission is extended and diffuse. Two compact features dominate the $H\alpha$ image located symmetrically with respect to the peak in the continuum image. They are connected by lower brightness emission.

Su et al.(1996) recently presented radio images of NGC 5929 obtained with MERLIN with a resolution of 0$''$.06. At radio wavelengths NGC 5929 shows a triple structure elongated along PA $\simeq$+60^o. The central component has a flat spectrum which leads to its identification with the self-absorbed radio nucleus (Wilson & Keel, 1989). The two lobes are located at 0.7$''$ SE and 0.6$''$ NW of the core, respectively.

3. Astrometry of the ground based images

The absolute astrometry of both plates and CCD frames is done utilizing reference stars. The insufficient density and the relatively bright magnitudes of the fundamental catalogs require the creation of a list of *secondary* reference stars within a suitable magnitude range and sufficiently close to the fainter target to be visible on larger scale, small field, plates or CCD frames (de Vegt 1979, Clements 1981). In our case, the absolute positions of the secondary references are established using the large-field refractor plates and a set of CAMC fundamental stars (Helmer & Morrison 1985, *Carlsberg Meridian Catalog* 1989, 1992, and 1993), which materialize the FK5 optical reference frame on the sky. Six CAMC stars were available for the *primary* calibration of the refractor plates. The metric properties of the focal plane of the refractor are such that a linear 3-constant polynomial model (for each coordinate) is adequate for an accurate transformation to the tangent plane, and therefore to the sky; magnitude and color terms are both negligible (Chiumiento et al. 1991 and references therein). The relevant errors characterizing the accuracy of the realization of the fundamental frame on the refractor plates are listed in Table 2.

Right ascensions and declinations on the FK5 system (equinox J2000 and epoch of plate) of 7 faint secondary astrometric standards within the CCD field-of-view were produced using the calibration just discussed. This same procedure, applied to the secondary standards, yields the plane-to-sky calibration for the CCD frame. The epoch difference among plates and CCD frames is less than two months; therefore, errors induced by undetected proper motions of the secondary reference stars are minimized. This is confirmed by the good agreement in Table 2 between the *estimates* in the third column of the first and second lines, and the residuals-derived values in the first column of lines three and four.

From the values in Table 2, it is evident that limitations to the astrometric calibrations come from both the image measuring errors (especially for the plates) and from the primary reference catalog, for which the contribution from the proper motions error becomes dominant for differences between catalog mean epoch and plate epoch on the order of 10 years.

Important for this work is to estimate the precision with which we can "position" any given measured images (either on the plates or on the CCD frames) within the FK5 frame. This error is the sum in quadrature of the centering error ϵ_{xy} and the *error of the transformation* which can be evaluated as $\epsilon_{tr} \sim \sqrt{n} \times \epsilon_{ref}/\sqrt{m}$, where ϵ_{ref} is the error in the primary reference catalog, n is the number of free parameters in the plate-to-field transformation used, and m is the number of primary reference stars; in our case, n = 3 and m = 6, $\epsilon_{tr} \sim$ 55 mas. The use of better catalogs (as with Hipparcos) would definitively improve on the 55 mas above. For example, with six Hipparcos stars the expected error on the transformation would be (including the proper motion error for an epoch difference of about 3 years) $\approx$ 5 mas! Therefore, with Hipparcos the expectation is that these calibrations will be limited, primarily, by the measuring errors,

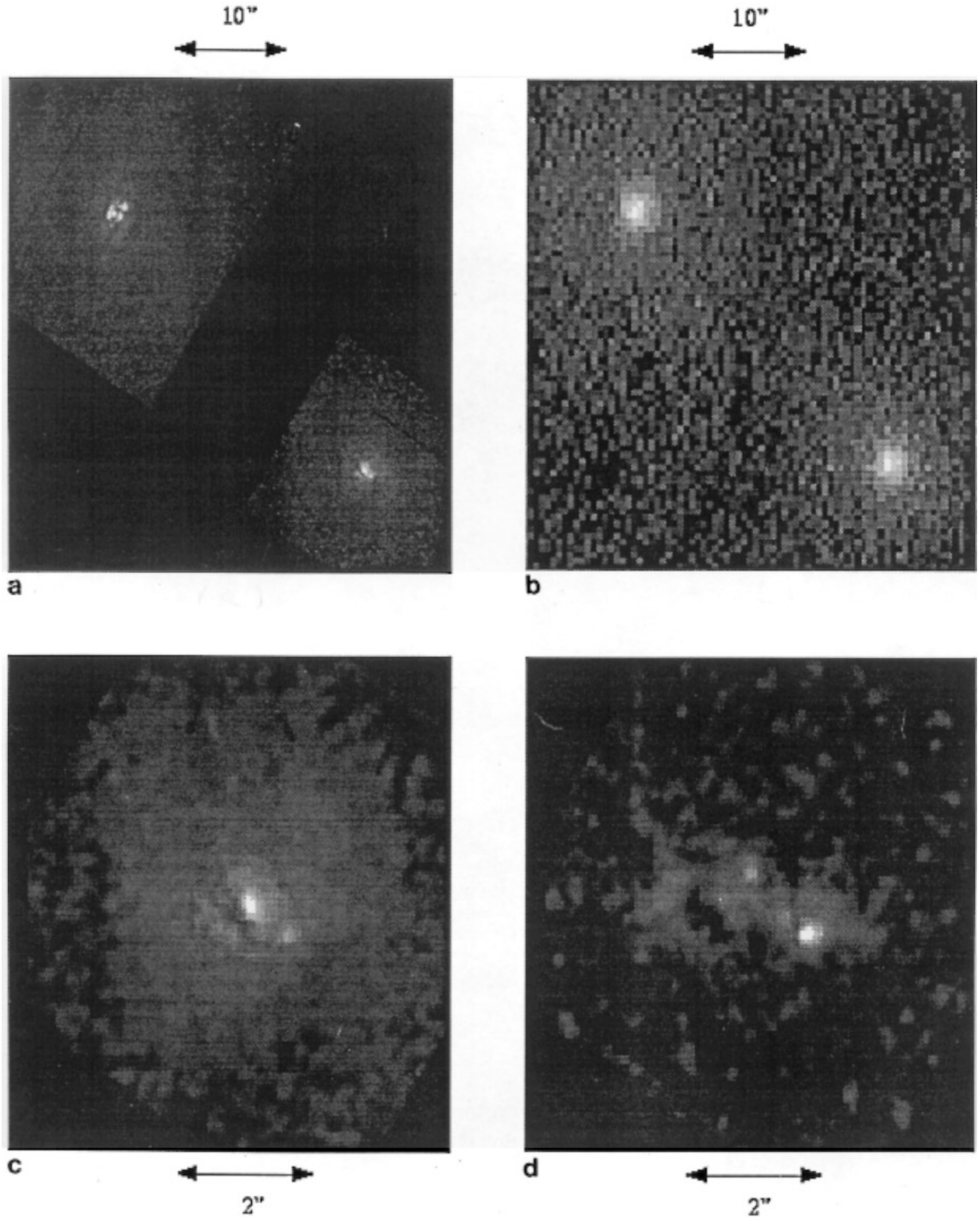

Fig. 1. a HST WF/PC-I and **b** ground based R band images of NGC 5929 and its companion NGC 5930; **c** continuum and **d** line emission ($H\alpha$ and [N II]) structure of NGC 5929

Table 1. Photographic plates and CCD frames centered on NGC 5929

Type	*Name*	*Date*	*Exp (min)*	Detector	*Filter*
plate	M1179	12 Aug 1994	30	103a-O	none
plate	M1180	12 Aug 1994	30	103a-O	none
frame	NGC5929R180s	22 Jun 1994	3	EEV CCD	R_C
frame	NGC5929R300s	22 Jun 1994	5	EEV CCD	R_C
frame	NGC5929R600s	22 Jun 1994	10	EEV CCD	R_C

at least until the degradation induced by the proper motion error settles in.

It is important to notice that ϵ_{tr} is *systematic*, in the sense that all measured images of the secondary reference stars will be affected by the *same* error (Eichhorn 1974). This explains why the ϵ_0 of the two least squares adjustments of the 600sec CCD frame reflects just the plate measuring errors (the CCD measuring error being negligible). Using the same argument as before, the error of a given CCD position relative to the secondary frame is ~ 20 mas[1]. Therefore, the *precision* with which we can "position" one of our ground based CCD images within the local FK5 frame is $\epsilon_{tr} \sim 58$ mas; this reduces to ~ 41 mas (*total* positional error) combining the two independent calibrations of the 600sec CCD frame. This error *does not* include yet any *local* systematic deviation of the optical frame from the radio one. This is discussed in Section 5 below. Finally, we need a procedure to transform the HST WF/PC-I pixels into pixels consistent with the ground based CCD image. This transformation introduces another term in the total error budget, which must be added in quadrature to the ϵ_{tr} value above.

Once this is accomplished, any given pixel of the WF/PC-I image can be mapped, thanks to the absolute calibration of the ground based CCD frame, onto the FK5 optical frame, i.e., the HST image can be *registered* onto such a frame. The HST-to-ground-based registration procedure is the subject of the next section.

Table 2. Astrometry error budget of ground based images. ϵ_0 is the mean error (per coordinate) as calculated from the residuals of the reference stars, ϵ_{ref} is the *estimated* mean error of the primary reference catalog, ϵ_{xy} the measuring (or centering) error, and ϵ_{tr} the error of the transformation plate-to-sky, as defined in the text. A good calibration is such that $\epsilon_0 \approx \sqrt{\epsilon_{xy}^2 + \epsilon_{ref}^2}$. Measuring errors are estimated at 30 mas (i.e., 1/15 pixel) for plate images, and 9 mas ($\sim$ 1/50 pixel) for CCD images

Image	ϵ_0	ϵ_{ref} *(mas)*	ϵ_{xy}	ϵ_{tr}
M1179	80	~ 75	30	~ 55
M1180	80	~ 75	30	~ 55
NGC5929R600sa[2]	35	~ 30	9	~ 20[1]
NGC5929R600sb[3]	30	~ 30	9	~ 20

[1] Relative to the secondary reference stars.
[2] Primary calibration from plate M1179.
[3] Primary calibration from plate M1180.

4. Registration of HST and ground based CCD images

Four parameters are needed to determine the orientation of the X,Y coordinate systems of HST and ground based images, namely the rotation angle, the scale factor and the shifts in the X and Y direction. They have been estimated using a cross correlation method. First, the deconvolved HST image has been convolved with the *observed* ground based point spread function. Then, the cross correlation function between this degraded HST image and the ground based image has been computed. The best estimates of the transformation parameters are obtained when the peak of the cross correlation function reaches the maximum amplitude.

For a successful application of this method, and particularly to determine the scale factor and the rotation angle, structures much greater than the resolution of the *ground based* image must be present in the HST image like, for example, a second object in the field; however, for nearby galaxies, the structure of the galaxy itself may be used. In this case the HST field of view also included NGC 5930.

This method assumes implicitly that these two images, the degraded HST image and the ground based one, are *identical* which, due to statistics and electronic noise, is never strictly the case. Also, the filter transmission, and therefore the point spread function, is slightly different. This leads to uncertainties in the registration which can be estimated as follow.

In the one-dimensional case, the cross correlation between two identical images is given by

$$C(x_0) = \int f(x - x_0) f(x) dx$$

where the integral is extended to the whole image. Its maximum is located at $x = 0$ where

$$C(0) = \int f(x)^2 dx$$

For small values of x the cross correlation function can be approximated as

$$C(x) \simeq C(0) + x \cdot C'(0) + \frac{1}{2} x^2 C''(0)$$

$C'(0)$ is equal to zero because the cross correlation has a maximum for $x = 0$; on the other hand

$$C''(0) = \int f''(x) f(x) dx = - \int f'(x)^2 dx$$

[1] In principle, this error can be reduced by measuring a larger set of secondary stars.

Table 3. Stability of the cross-correlation between HST and ground based images. *Offset* represents the shift from the calculated optimal alignment between the two frames

Offset (pixel)	*Error* (pixel)	*Offset* (pixel)	*Error* (pixel)
-1.0	0.93	-0.8	0.74
-0.6	0.52	-0.4	0.31
-0.2	0.11	0.0	0.10
0.2	0.25	0.4	0.42
0.6	0.62	0.8	0.76
1.0	0.93		

Then

$$C(x) \simeq \int f(x)^2 dx - \frac{1}{2}x^2 \int f'(x)^2 dx$$

If the images are not identical, the cross correlation function is given by

$$D(x_0) = \int f(x - x_0)g(x)dx = C(x_0) + \int f(x - x_0)h(x)dx$$

where $h(x) = g(x) - f(x)$.

For small values of x, the derivative of $D(x)$ is given by

$$D'(x) \simeq D'(0) + xD''(0)$$

where

$$D'(0) = -\int f'(x)h(x)dx$$

and

$$D''(0) = -\int f'(x)^2 dx + \int f''(x)h(x)dx$$

The maximum of the correlation function is then located at

$$x_{max} \simeq \frac{-\int f'(x)h(x)dx}{\int f'(x)^2 dx - \int f''(x)h(x)dx}$$

This approximation is valid as long as $|h(x)| = |g(x) - f(x)| \ll |f(x)|$.

All these quantities can be derived directly from the images and from these we obtain an estimate of the displacement of the peak of the correlation function x_{max} with respect to the optimal alignment, i.e. the error in the registration. In our case the error is 0.10 pixels in the ground based image, corresponding to 47 mas. The reliability of this method has been checked empirically by shifting the images from their optimal alignment by $\pm$ 1 pixels at 0.2 pixels steps in the X direction and then estimating the errors, which are given in Table 3. The close correspondence of the offsets with the errors testifies to the reliability of this method.

The error estimate has also been performed on the other two ground based CCD images taken with shorter exposure time. The alignment errors are 48 and 40 mas, similar to those obtained with the longer exposure. It therefore appears that the statistical errors are not the main source of uncertainty. Systematic differences between HST and ground based images, as for example the transmission curve of the F718M filter slightly narrower than the standard R_C (Cousins R) filter, might explain this result.

5. Radio and optical reference systems

The final FK5 optical position of NGC 5929, measured as the point of maximum correlation between the ground -based frame and the "degraded" WF/PC-I continuum image, is α(J2000) = $15^h\ 26^m\ 6^s.1654$ and δ(J2000) = + 41° 40' 14".418. This position is consistent with the coordinate system of the contour plots of Figures 2a and 2b, and its estimated total error is $\sqrt{41^2 + 47^2}$ $\simeq$ 62 mas. This error measures the precision of our optical registration. However, a *systematic* deviation between optical and radio frames is expected. Both, an error in the RA zero-point alignment of the radio frame to the FK5, and local "regional" deviations of the two systems are expected. Assuming that the right ascension zero-point of MERLIN maps has been set via one of the currently adopted procedures for the realization of what is called today the International Celestial Reference Frame (ICRF) [by using the standard source 3C 273 or by an adjustment to known FK5 positions of a set of compact radio sources (see for example Ma et al. 1990)], the local optical-to-radio systematic deviations can be of the order of 20 mas or larger. A recent accurate registration of the radio and optical images of SN 1987A using preliminary Hipparcos data (Reynolds et al. 1995) has shown, thanks to a direct measure of the effect, that the local systematic deviation between the two systems is $\simeq$ 22 mas in declination. We conclude that a systematic shift of about 20 mas should be included in the calculation of the final error of the optical position. This shift *adds* directly to the error of the optical position and not to its variance.

A drastic improvement on these residual systematic deviations is expected following the radio-optical link of the Hipparcos catalog. The final accuracy is anticipated in Lindegren and Kovalevsky (1995) at the 0.5 mas level (for the positional system; 0.5 mas yr^{-1} for the proper motion system).

6. Results and discussion

By combining the uncertainty in the absolute astrometry of the ground based image with the accuracy of the registration of the HST image, we find that the absolute astrometry of the HST image has been obtained to $\simeq$ 62 mas.

Finally, to complete the error budget analysis of the optical-to-radio registration, we have to include the local systematic difference between the two systems (20 mas, see above) and the intrinsic precision of MERLIN observations, which is estimated at 50 mas. Therefore, the total error of our registration of NGC 5929 is estimated at $\sim$ 100 mas.

In Fig. 2 the contours from the MERLIN radio image by Su et al. (1996) are overlaid onto the HST line and continuum images. The cross on the lower right corner represents the uncertainty in the registration. The radio core falls within the nuclear dust lane. No optical counterpart to the radio nucleus is seen. In the framework of the Unified model for Seyfert galaxies (e.g. Antonucci, 1993), the active nucleus of NGC 5929 is obscured at optical wavelength by a circumnuclear torus. As observed in several Seyfert 2 galaxies (e.g. Capetti et al., 1996), nuclear dust lanes are often associated with the obscuring torus. The nucleus

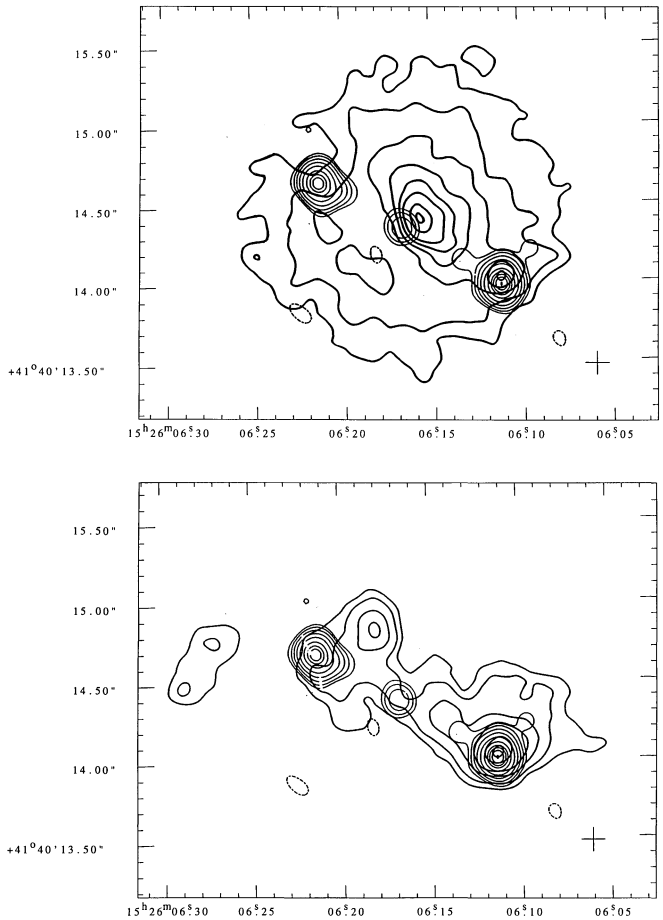

Fig. 2a and b. contours from the MERLIN radio image by Su et al. (1996) overlaid onto the HST WF/PC-I contour image in **a** the continuum and **b** the line emission. The cross on the lower right corner represents the uncertainty in the registration, 80 mas.

itself is expected to be offset from the peak of emission in a direction perpendicular to the dust lane orientation, in agreement with our results.

Fig. 2b confirms the association of the line ($H\alpha$ and [N II]) emitting component with the radio lobes already noted by Whittle et al. (1986) and Bower et al. (1994), and which is commonly observed in Seyfert galaxies (Capetti et al., 1996). In particular the SW radio and optical components are essentially coincident. The lower brightness line emission linking the two main knots is closely aligned with the radio axis.

7. Summary and conclusions

We present a method to improve the absolute astrometry of HST images. The method has been applied as a test case to the Seyfert 2 galaxies NGC 5929 to register the HST and MERLIN images. The astrometry of the HST image is accurate to 62 mas, while the error in the final registration with the radio image appears $\sim$ 100 mas. Systematic differences between the HST and ground based images are probably the main source of uncertainty in their registration, which can be improved by carefully planning the ground based observations to better reproduce the HST observational parameters. However, the HST absolute astrometry would be only marginally improved given the error of 41 mas in the reference ground based image. Similarly, the registration between HST and radio images is affected by the difference between the radio and optical reference frames and by the accuracy on the positions of the radio phase calibrators. For these reasons, a significant reduction in the error budget of this method is not anticipated until ground based techniques, reference catalogs, and the radio-optical link, are all sensibly improved. The forthcoming Hipparcos catalog will, albeit partially, drastically improve on the present situation.

Acknowledgements. We thank B.M. Lasker for digitizing the photographic plates; G. Massone and L. Lanteri for their help with the ground based observations and plate mesurements. Finally, we wish to thank Dr. L.V. Morrison for his careful refereeing.

A.C. acknowledges financial support from the ST ScI grants GO-4666 and GO-3594.

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