Astrometry of Comet 46P/Wirtanen at ESO: Preparation of ESA's ROSETTA Mission

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1. A New European Spacecraft to a Comet

1.1 The ROSETTA mission

Comets play an important role in the studies of the solar system and its origin, because they are believed to contain matter in a primordial form. After the success of the GIOTTO flyby at comet 1P/Halley in 1986, ESA plans to send a second spacecraft named “ROSETTA” to another comet, 46P/Wirtanen, for a more thorough investigation of a cometary nucleus and its physico-chemical nature. After its launch in 2003 and two asteroid flybys during the cruise phase to the prime target, ROSETTA will rendez-vous with 46P/Wirtanen in 2011 and will orbit the comet in a distance of 10 to 50 km until at least its subsequent perihelion passage in 2013. During this orbiting phase it will perform *in situ* experiments of the coma, remote sensing of the nucleus and, most important, it will also place a lander called “RoLand” with several scientific experiments on the nucleus of the comet. The main scientific objectives of the mission are (see also [16]): global characterisation of the nucleus and its dynamic properties, chemical composition, physical properties and interrelation of volatiles and refractories in the nucleus.

ROSETTA shall help answering the questions of the origin of comets, the relationship between cometary and interstellar material and its implications with regard to the origin of the Solar System.

The probe is named after the Rosetta stone which covers one text in three ancient scripts (hieroglyphs, demotic and Greek). After its discovery in 1799 it was possible to decipher the Egyptian hieroglyphs in 1822. Now the stone is on display in the British Museum in London, UK [13].

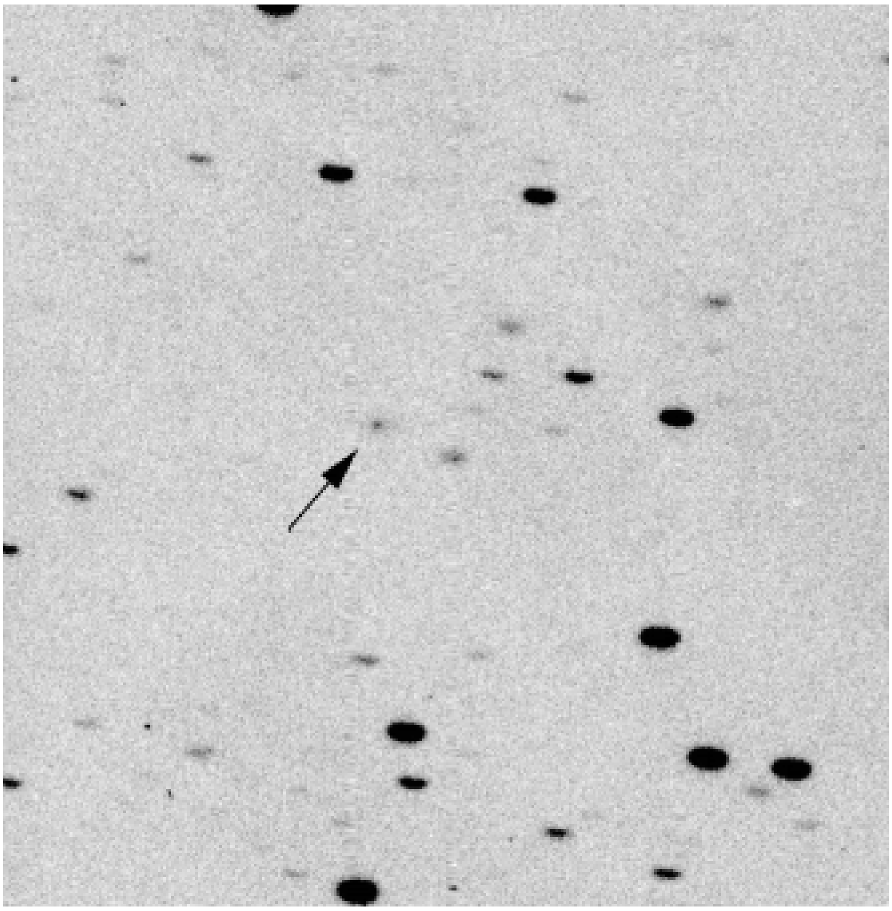

Figure 1: A 600 sec R filter image of comet 46P/Wirtanen taken on April 25, 1996, at the Danish 1.5-m telescope. North is up and east to the left. The image shows a field of view of 3.3′. Wirtanen is marked with an arrow. Note the elongated stellar images due to guiding with respect to the comet.

1.2 The target comet: 46P/Wirtanen

The comet was discovered on January 17, 1948, at Lick Observatory, USA, by Carl A. Wirtanen. With an orbital period of about 5 years, it belongs to the so-called Jupiter family comets, the orbits of which are subject to repeated close encounters with the planet Jupiter (then altering the orbit parameters severely). The most recent perihelion passage of 46P/Wirtanen took place on March 14, 1997. The parameters of the current orbit of the comet from [7] (see also [14]) are summarized in Table 1.

During its current revolution, the comet was recovered in 1995 – with a magnitude of about 24.5 in a very crowded star field close to the centre of the Milky Way – at ESO La Silla [1, 2]. The comet was found to have the smallest nucleus known so far, i.e. about 600–700 m in radius (measured first by [2] and confirmed later by HST observations [5]). Recent work based on some of our data reveals a light curve which hints at a rotation period of almost 7 hours [3].

The small size of 46P/Wirtanen makes the mission more difficult: A larger mass would be helpful in keeping the spacecraft in orbit around the nucleus and dropping the lander onto the surface.

TABLE 1: Orbital elements of comet Wirtanen. The coordinates are given with respect to equinox 2000.0.

Date of perihelion	1997 03 14.14299
Distance at perihelion	1.0637469 AU
Perihelion Argument	356.34322°
Ascending Node	82.20387°
Inclination	11.72255°
Eccentricity	0.6567490
Orbital Period	5.46 years

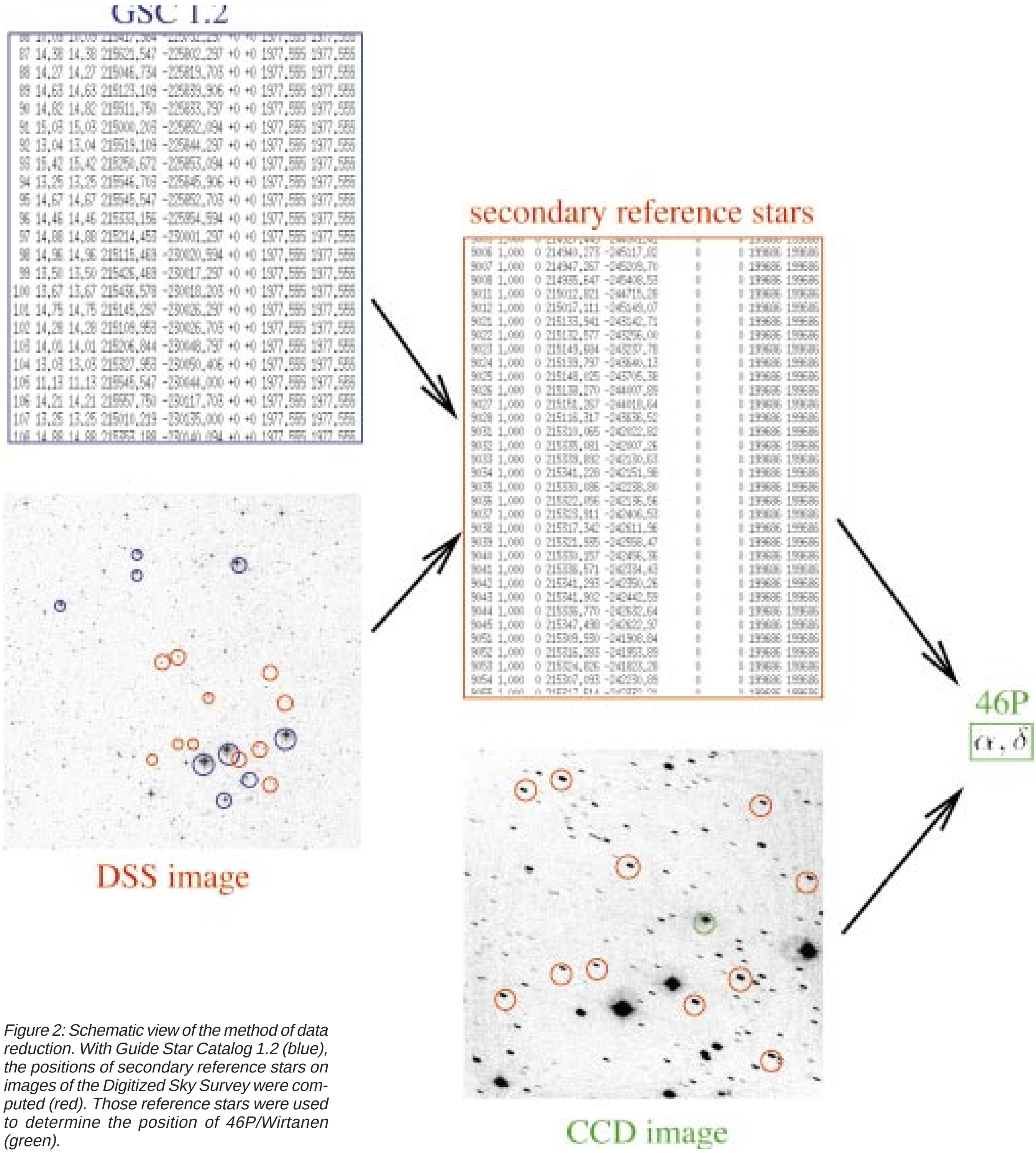

Figure 2: Schematic view of the method of data reduction. With Guide Star Catalog 1.2 (blue), the positions of secondary reference stars on images of the Digitized Sky Survey were computed (red). Those reference stars were used to determine the position of 46P/Wirtanen (green).

2. Astrometry Support for the Cometary Mission

For mission-planning purposes, in particular for an economic planning of the use of manoeuvre propellant during the cruise phase to the comet, it is important to know the object's orbit with a very high accuracy. The orbit characterisation becomes particularity difficult because of the non-gravitational forces. These perturbations of the orbit are caused by the outgasing of the cometary nucleus. Therefore, astrometric positions all along the orbit and over several orbital revolutions are required for an accurate orbit determination which then can be used for proper mission planning of ROSETTA. In the case of 46P/Wirtanen, it is a difficult task to obtain such measurements because the object is very faint due to its large distance from the Earth and the Sun during most of its orbit.

The only possibility to observe distant and faint moving objects and to measure their positions accurately and in a suitable time (the exposure times must not be arbitrarily long because of the orbital motion of the target object!) is given by the use of CCD imaging. However, this leads to the problem that due to the small field sizes of CCDs, the number of reference stars within the field is too small for a good transformation from the CCD positions to the celestial coordinates.

In the following, we present a recently developed technique which is tailored for the determination of very accurate astrometric positions of faint solar-system objects on small-sized CCD frames. The positions of 46P/Wirtanen, which we obtained from La Silla observations in 1996, were used to improve the orbit parameters of the comet in support of ESA's ROSETTA mission.

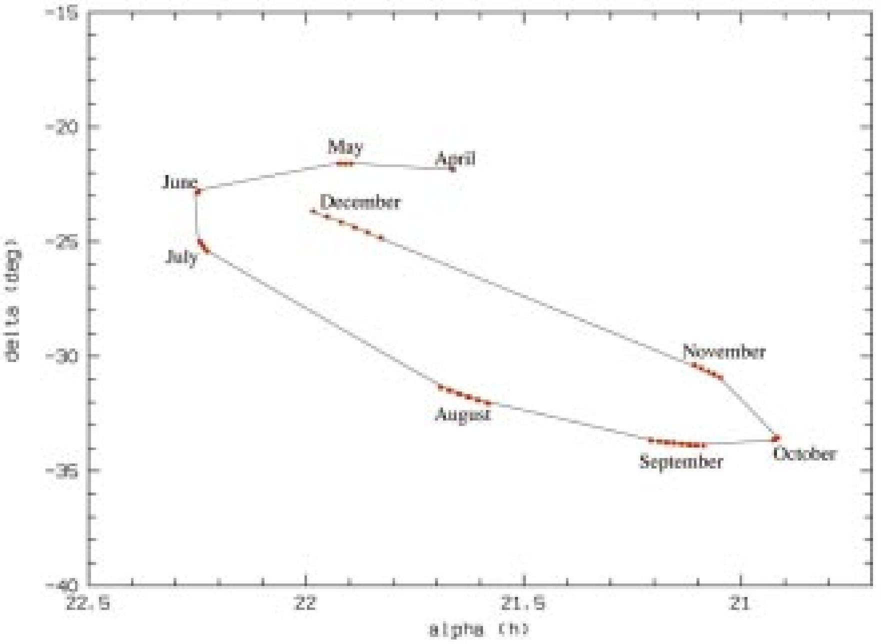

Figure 3: Trajectory of comet 46P/Wirtanen during April to December 1996. Note that the coordinates given are topocentric and therefore superimposed by the Earth's parallax.

3. The ESO Observations of the Comet in 1996

The observations used in our analysis were collected at the ESO La Silla observatory in Chile in the context of a coordinated campaign for the assessment of the nucleus properties and the coma activity of 46P/Wirtanen in preparation of the ROSETTA mission. The CCD images were taken in 1996 by various observers (see Table 2) at two different telescopes, the 1.54-m Danish telescope equipped with DFOSC (2k × 2k CCD with a pixel size of 0.4″) and the ESO/MPG 2.2-m telescope equipped with EFOSC2 (until July 1996 1k × 1k CCD of pixel size 0.32″, thereafter 2k × 2k CCD of pixel size 0.27″). With these telescope-instrument combinations, one obtains images with a field of view of 13.7′ (DFOSC) and 5.5′ or 9′ (EFOSC2), respectively. Due to CCD artefacts in DFOSC, only the inner 1500 × 1500 pixels were useful for our measurements. The images of the comet were exposed through broadband BVR filters with different durations ranging from 30s to 600s (depending on the comet's brightness and motion rate). As the telescope was guided on the target object, the stellar images were more or less elongated, depending on the exposure times and apparent velocity of the comet.

The main goal of the astrometry part of the programme was to measure the positions of the comet over the whole orbit arc from a distance close to the point where ROSETTA will start its science mission until almost to perihelion. The early observation phase when the comet was fainter than 20 mag imposed the challenge to measure the position of a very faint, hardly detectable object on a scary star background. Towards the end of our observing period, its brightness had increased to ~ 14 mag which made it a more comfortable object, but now also with a much higher motion rate since it was closer to the Earth and the Sun.

From the several hundred frames of the comet obtained in 1996 we selected a total of 79 images (all taken through Bessell R filter) for the astrometric measurements. An example image from the first run in April 1996 is shown in Figure 1.

TABLE 2: The ESO imaging campaign of comet 46P/Wirtanen. Besides the information on the observing runs themselves, Wirtanen's motion rate υ, distances r and Δ from Sun and Earth, respectively, are given. The values are averaged over the monthly observing periods.

Date	Δ [AU]	r[AU]	υ [″/h]	telescope	observer
25.04.96	3.4	3.3	33	1.5-m DK	Böhnhardt, Rauer
11.–13.05.96	3.1	3.2	28	2.2-m	West
18.–19.06.96	2.3	3.0	14	1.5-m DK	Jorda, Schwehm
09.–12.07.96	1.9	2.8	23	2.2-m	Peschke
18.–23.08.96	1.2	2.5	46	1.5-m DK	Thomas, Rauer, Böhnhardt
10.–17.09.96	1.5	2.3	33	2.2-m	Schulz, Tozzi
02.–04.10.96	1.5	2.2	12	1.5-m DK	Rauer
01.–05.11.96	1.6	1.9	29	1.5-m DK	Böhnhardt
06.–08.12.96	1.7	1.6	71	1.5-m DK	Cremonese, Rembor
08.–11.12.96	1.7	1.6	73	2.2-m	Rembor, Cremonese

4. The Astrometric Data Reduction

Before the astrometric measurements were performed, all images were bias subtracted and flat-fielded. Due to the small fields of the images, classical reference stars from catalogues like the Guide Star Catalog (GSC) [6], PPM Star Catalogue [10, 11], etc. do not cover the sky sufficiently dense to be used directly for the astrometric processing of the frames. In addition, most of them were saturated on the CCD images due to the relatively long exposure times used for depicting the comet. Therefore, we developed a concept for the determination of the positions of the comet by the use of *secondary* reference stars determined from rectangular positions of stars on the Digitized Sky Survey (DSS) [9]: for each CCD frame, we derived positions of 10 to 15 secondary reference stars (covered both by the CCD image and DSS) with respect to about 30 nearby GSC stars.

For the determination of the rectangular pixel coordinates of the objects on the CCD frames and the DSS we used the `imexamine` routine of the IRAF software package. Earlier tests of this routine had shown that a positional accuracy of about 0.1 to 0.2 pixel can be achieved [4]. This value corresponds to a positional uncertainty of less than 0.1″ (corresponding to about 300 km at a distance of 5 AU which is approximately Wirtanen's distance during the first measurements), which provides a sufficient accuracy for the astrometry of comets. This uncertainty does not play any role for the 2011 rendez-vous with ROSETTA, because the non-gravitational forces do not allow to make an orbit prediction of the comet to this level of accuracy over several revolutions (and the comet will pass perihelion twice before ROSETTA will arrive).

The improved version 1.2 of the GSC [15] was taken for the reduction. Since the GSC does not contain proper motions and the epochs of the DSS and GSC differ, we omitted all stars showing deviations larger than 3σ from the root mean square (rms) between measurements and catalogue.

In a first step, the coordinates of the secondary reference stars on the DSS images were determined with respect to the GSC stars with a third order polynomial approximation (i.e. 10 plate constants). Secondly, the comet's position was computed using the images of the secondary reference stars on the CCD frames. Figure 2 sketches this method.

5. The Results and Discussion

Figure 3 shows the apparent motion of comet Wirtanen on the sky during the time of our 1996 observations.

The positions obtained [12] revealed a larger than expected offset from the previously predicted positions. This indicates that the data gathered during earlier apparitions may be too inaccurate and/or badly sampled to compute a sufficiently precise long-term orbit of the comet.

The rms of the deviations between DSS measurements and the catalogue positions was less than 0.2″ corresponding to an uncertainty of 0.1″ for the secondary reference stars. We obtained a rms of the deviations between catalogue and rectangular coordinates on the CCD frames of better than 0.2″.

For the accuracy of the final positions, we have to consider contributions from different sources. First of all, the comet appeared as a diffuse object (and not as a point-like star), which leads to problems in finding the "centre" of the comet. Another possible error source is the influence of higher-order image distortions due to imperfect optics of the telescope/instrument system. However, since in our images the comet was located essentially in the central region of the frames and since the secondary reference stars were distributed evenly over the frame, we think that in our data this effect will be small. A third problem lies in the motion of the comet with respect to the star background and the possible trailing of the comet images due to imperfect telescope guiding, which lead to elongated images – especially for the long exposures (up to 600s). Moreover, epoch differences of observations and catalogues in combination with the proper motions of the stars could cause systematic deviations of these positions. All these effects are difficult to evaluate. However, the orbit calculation of the comet based on our and other positions can give an estimation of the accuracy of our astrometry of the comet.

The data were compared with an orbit calculated by T. Morley (ESA) [8]. He used all data available from November 1985 until December 1996, i.e. three apparitions of Wirtanen, including our own data. He also took into account the non-gravitational forces which he extrapolated from the previous apparitions (Non-gravitational forces can only be determined *a posteriori*, i.e. long after the corresponding perihelion passage).

From a comparison of our results with this orbit we obtained "O–C" (observed – calculated) deviations of +0.27″±0.85″ in α and +0.22″±0.32″ in δ. The larger deviations in right ascension are mainly seen in the observations in August and September 1996. During this period the comet had a large motion in right ascension, which caused elongated images and possibly the larger uncertainty of the positions. The deviations in right ascension and declination are shown in Figures 4 and 5.

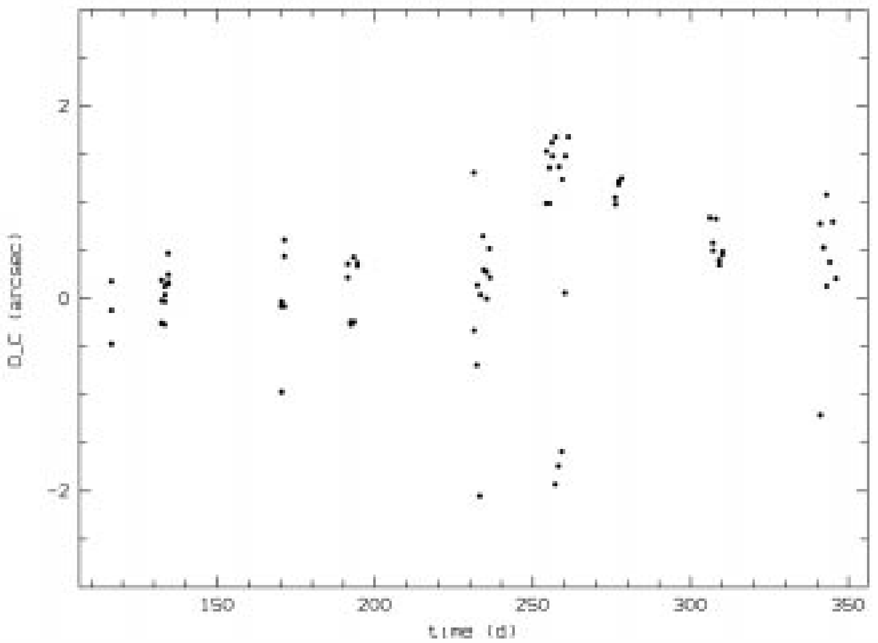

Figure 4: Plot of the O–C values in right ascension. The errors are plotted with respect to the time of observation, given in days of the year 1996. Note the high scatter of the values especially around 250 d (August/September).

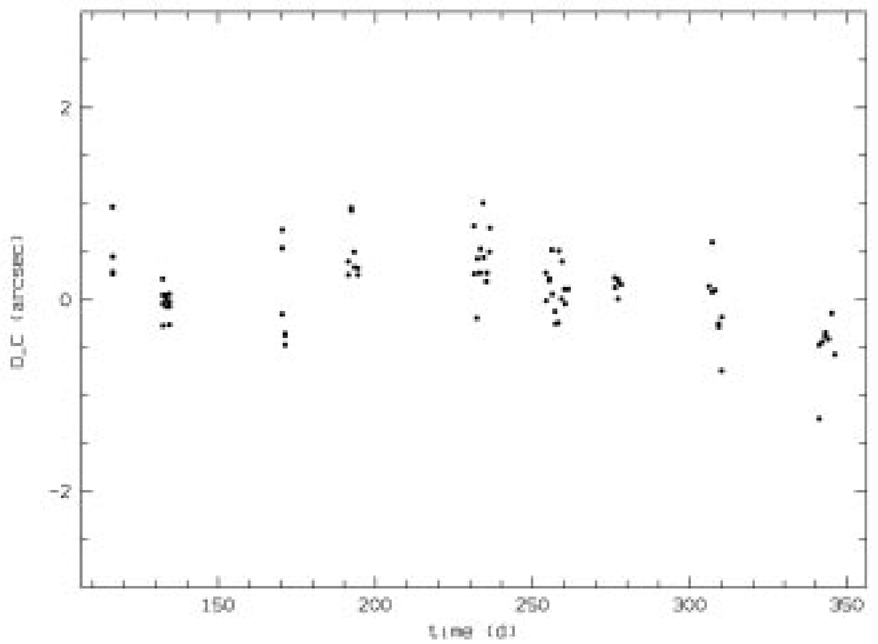

Figure 5: Plot of the O–C values in declination. It seems that there is a systematic trend of the O–C values with time. Such effects can be due to an imperfect modelling of the perturbing non-gravitational forces.

6. Outlook and Summary

46P/Wirtanen will be monitored over the following years by many observatories. This includes ESO, but it can be expected that this will be on a smaller level than during the 1996 campaign. The orbit will be continuously improved with new data as well as the model for the non-gravitational forces. As the ROSETTA probe will follow a flight path which lets it catch up slowly with the comet, the ground-based observations should already lead to an ephemeris which is sufficiently precise to reach the target with very slight in-flight corrections of the trajectory. By that time, also the ESO support can be expected to be on a much higher level again. And in the final phase of the approach, an on-board camera will take additional images of the comet for a fine-tuning of the manoeuvres.

Our work plays a significant role for the project for two reasons: Firstly, CCD imaging gave the chance to observe Wirtanen in the remote part of the orbit which increased the understanding of the orbit itself and the non-gravitational forces, and on the other hand, our method to use the DSS as a coupler between the coarse reference catalogues and the CCD fields allows astrometric work on small fields of any part of the sky. Of course, the method is not sufficient for high-precision astrometry (e.g. proper-motion studies), but it can be very well used for CCD astrometry of faint solar-system bodies.

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[13] http://www.british-museum.ac.uk/highligh.html
[14] http://nssdc.gsfc.nasa.gov/planetary/factsheet/cometfact.html
[15] http://www-gsss.stsci.edu/gsc/gsc12/description.html
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NTT Archives: the Lyman α Profile of the Radio Galaxy 1243+036 Revisited

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Abstract

All observations of very high redshift radio galaxies attest to a highly complex interaction between large-scale astrophysical processes as violent and diverse as that of nuclear activity and of cosmogonic star formation. Lyα is seen in emission over scales exceeding galactic sizes and its resonant nature leads by itself to a wide range of phenomena such as absorption lines due to intervening H I gas layers of very small columns, or enhanced dust extinction due to the manifold increase in path length traversed before escape. The resonant nature of Lyα can also manifest itself in emission through the process of Fermi acceleration across a shock discontinuity which leads to a large blueshift of the line photons. We propose that such a process is at work in the radio galaxy 1243+036 (z = 3.6) and can account for the three narrow emission peaks present on the blue side of the profile. The ultimate source of the photons present in those peaks likely consists of a jet-induced starburst of ≥ 5 10^7 $M_\odot$ situated at the position of the radio jet bend. Our investigations illustrate one possible use of the user friendly archival database developed by ESO.

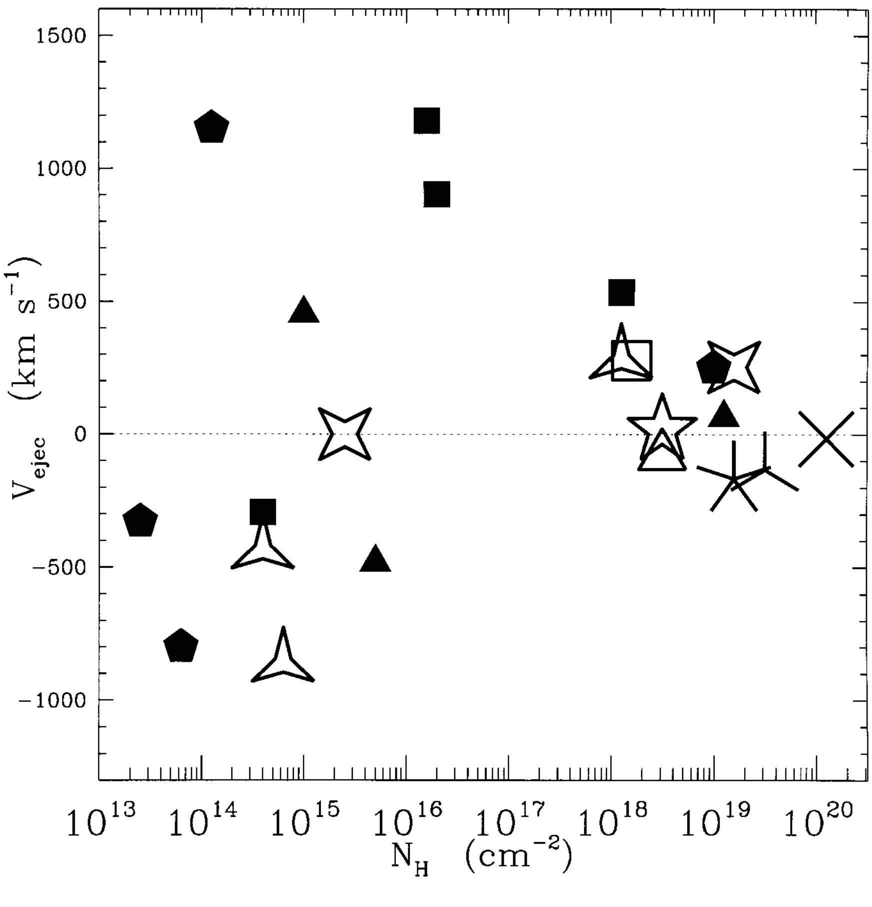

Figure 1: Velocity shifts of the absorbers relative to line centre as measured by van Ojik et al. (1997). Distinct symbols are used to distinguish different objects. For instance, all the four absorbers of 0828+193 are represented by solid squares. Negative and positive ejection velocities are of comparable likelihood. The figure does not contain the absorption dips reported in 1243+036.

1. General Context

Lyman α is the strongest emission line observed in High-Redshift Radio Galaxies (HZRG). Although the brightness of the line reaches a maximum towards the nucleus, most of the emission is spatial-