The EROS Search for Dark Halo Objects

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1. Introduction

It is widely believed that the flat rotation curves observed for spiral galaxies like our own indicate that such galaxies are contained in a "halo" of dark matter [1]. While the mass of the dark halos should be as much as ten times that of the visible parts of galaxies, the composition of the halos is not known. Candidates range from hypothetical weakly interacting elementary particles to dark astronomical objects like brown dwarfs or black holes. The identification of the halo constituents would have profound implications for cosmology and theories of galaxy formation.

Paczyński [2] suggested that dark astronomical objects in our Halo could be detected by monitoring the brightness of individual stars in the Large Magellanic Cloud (LMC). Because of the gravitational deflection of light, if a massive Halo object passes near the line-of-sight to an LMC star, the amount of light received from this star by the observer will be increased. The amplification is a function of the "impact parameter" r_0, i.e. the minimum distance between the undeflected line-of-sight and the massive deflector. In terms of the normalized impact parameter *u*, the amplification is

$$A(u = r_0/R_E) = \frac{u^2+2}{u\sqrt{u^2+4}}$$

where R_E, the "Einstein radius", is a function of the deflector's mass M, the observer-deflector distance D_d and observer-star distance D_S:

$$R_E^2 = \frac{4GM}{c^2} D_d\,(1 - D_d/D_s)\,.$$

The size of the amplification is greater than 0.3 magnitude if the impact parameter is less than the Einstein radius of the deflector ($u < 1$). The probability of such an amplification, for a given star and at any given time, is simply the probability that this star lies behind a circle of area πR_E^2 centred on any deflector between us and the star. Since R_E^2 is proportional to the deflector mass while the number of deflectors in the Halo is inversely proportional to their mass, this probability depends only on the total dark matter mass along the line-of-sight and not on the individual deflector masses. This probability turns out to be of the order of the square of the galactic rotation velocity devided by the speed of light, or about 10^{-6}. A more precise estimate gives a probability of about 0.5 $\times 10^{-6}$ for amplifications greater than 0.3 magnitude. This figure was calculated assuming a spherical "isothermal" halo of total mass $4 \times 10^{11}\ M_\odot$ at distances from the Galactic centre less than the distance to the LMC. This mass would produce a flat rotation curve at the observed Galactic circular speed of 220 km s^{-1}.

Since the observer, star and deflector are in relative motion, a sizeable amplification lasts for a time of order R_E/v_T where v_T is the relative transverse velocity of the deflector. For the lensing of stars in the LMC by objects in our Halo, these relative speeds are of order 200 km s^{-1} and the most probable lensing time is roughly:

$$r = 70 \text{ days} \sqrt{\frac{M}{M_\odot}}\,. \qquad (1)$$

(We have taken the "lensing time" to be the time during which the amplification is greater than 0.3 magnitude.) The characteristic light curve is shown in Figure 1. The distribution of lensing times for a given deflector mass is expected to resemble that shown in Figure 2.

Since τ is proportional to $\sqrt{M}$, the number of microlensing events expected for a fixed observation time is inversely proportional to $\sqrt{M}$. To observe one event with characteristic time τ, the product of the number of stars monitored and the effective observing time must be of order $10^6\tau$. This can be achieved if the Halo consists of unseen objects in the mass range one to 10^{-7} solar masses, corresponding to characteristic times of a few months to a few hours. This range of masses covers hydrogenous objects that are both too light to burn hydrogen ($M < 0.07\ M_\odot$) and too big to have evaporated since their formation in the early Universe ($M > 10^{-7}\ M_\odot$) [3].

To be sensitive to amplifications of order 0.3 magnitude, the photometric precision per measurement should be of order or better than 0.1 magnitude. Rejection of intrinsically variable stars can be achieved, in principle, by requiring that light curves be symmetric, achromatic and exhibit a single extremum (the amplification events should not be repeated).

Following discussions in 1989 led by Charles Alcock of Livermore, two groups have initiated observation programmes to reach the required sensitivity. One group is a Livermore-Berkeley (Center for Particle Astrophysics)-Mount Stromlo-San Diego-Santa Barbara collaboration and is observing the LMC from Mount Stromlo, Australia [4]. The other group, called EROS (Expérience de Recherche d'Objets Sombres), is our own collaboration of particle physicists and astronomers, started in January 1990. We are observing the LMC from the ESO observatory in La Silla, Chile [5].

EROS consists of two programmes. The first is designed to be sensitive primarily to deflector masses in the range $10^{-4}M_\odot < M < 10^{-1}M_\odot$ corresponding to mean lensing durations in the range 1 day $< \tau <$ 30 days. It uses Schmidt plates of the LMC and permits us to monitor about ten million stars over a period of several years. (About

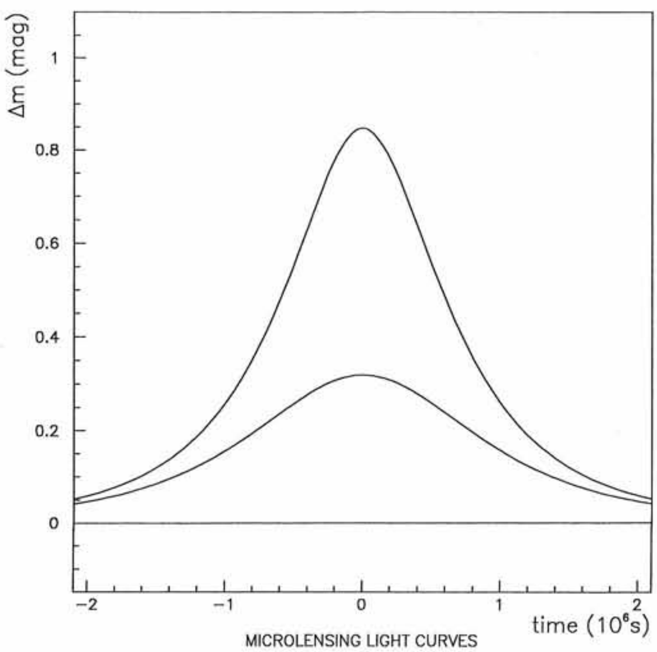


Figure 1: *The theoretical light curves for impact parameters of 0.5 R_E (upper curve) and 1.0 R_E (lower curve). The time dependence was calculated assuming a deflector of mass $10^{-2} M_\odot$, 10 kpc from the Sun, moving with a relative transverse speed of 160 km/s.*

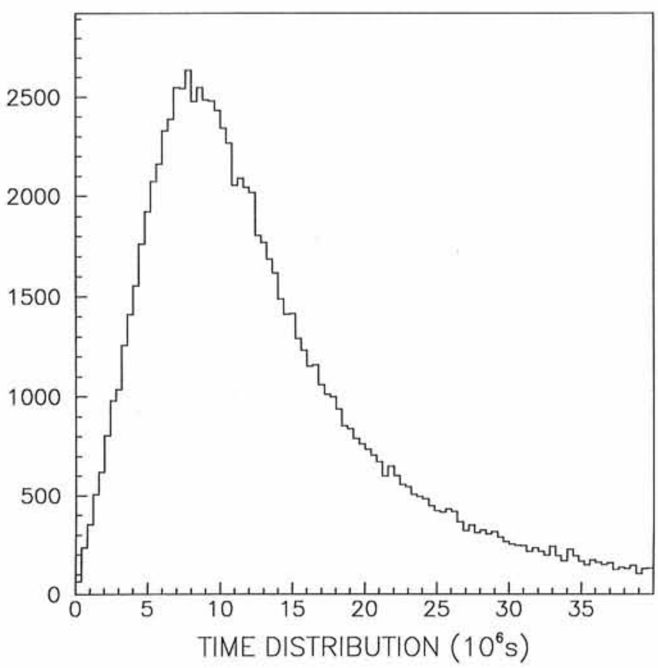


Figure 2: *Distribution of lensing times for an "isothermal" Halo composed of 1 $M_\odot$ deflectors, in units of 10^6 seconds. The lensing time is taken to be the interval during which the amplification is greater than 0.3 magnitude. For other masses, it scales with the square root of the deflector mass.*

half of these stars are bright enough to be monitored sufficiently accurately to observe variations at the 0.3 magnitude level.) The second programme is designed to be sensitive primarily to deflector masses in the range $10^{-7} M_\odot < M < 10^{-3} M_\odot$ corresponding to event durations in the range 1 hour $< \tau <$ 3 days. It uses a large CCD mosaic on a dedicated telescope to monitor about 150,000 stars every 20 minutes.

This report describes the present status of EROS and gives some preliminary results. Prospects for the future are also discussed.

2. The CCD Programme

The CCD programme started at La Silla in December 1990 with a one-month feasibility study during which we observed the LMC bar with the 40-cm GPO refracting telescope. We used a camera consisting of one 576 × 405 pixels Thomson CCD chip giving a field of 11 × 8 arcmin. A total of 63 images of one dense field of the LMC bar was taken. The strategy of using alternating blue and red filters was established.

Following this short study, we decided to replace the refracting telescope with a 40-cm reflector (f/10) mounted on the back of the GPO as shown in Figure 3. This allowed us to use wide band filters (centred at 480 nm and 670 nm) with the consequent reduction of exposure times. We also constructed a wide field CCD camera [6] with sixteen buttable 576 × 405 pixels Thomson THX 31157 CCDs (Fig. 4). The total field of this camera is about 1° × 0.5° and is oriented so as to follow the LMC bar.

Data acquisition and camera control are performed with a VME system based on a 68030 processor. The data taken during one night are stored on a

Figure 3: *The 40-cm reflector mounted on the GPO at La Silla.*

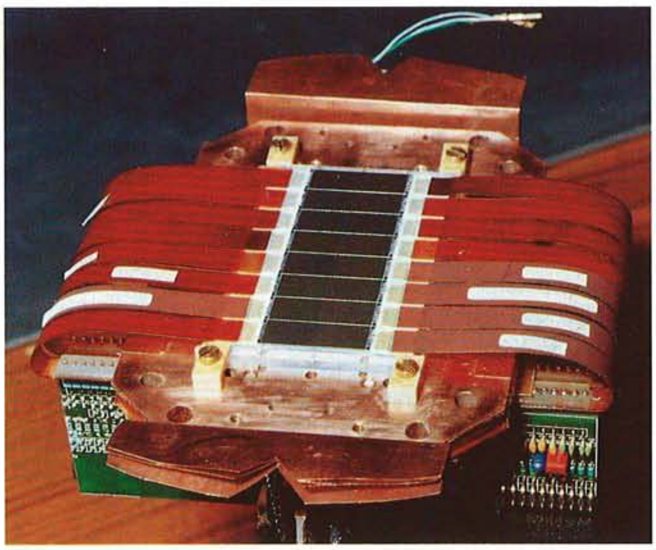


Figure 4: *The CCD mosaic.*

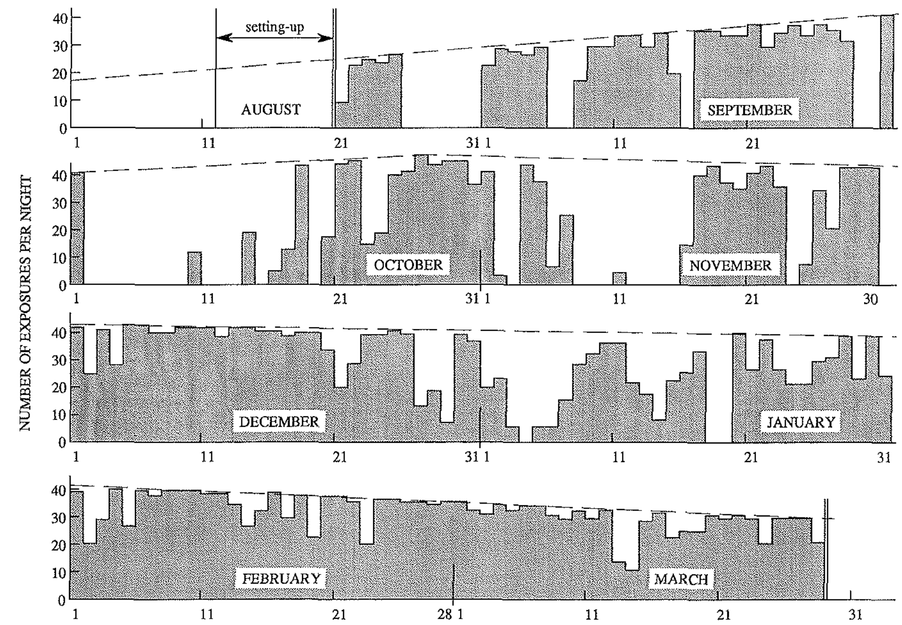


Figure 5: *Number of CCD images per night (1992–93 season).*

DAT tape. The system is also linked to a DS 5000/200 workstation for preliminary on-line analysis.

We have used this set up to observe one very populated field of the LMC from December 1991 to March 1992 and again from August 1992 to March 1993. The corners of the field are at ($\alpha = 5^h29^m$, $\delta = -69°28'$), ($\alpha = 5^h28^m$, $\delta = -69°54'$), ($\alpha = 5^h15^m$, $\delta = -69°41'$), and ($\alpha = 5^h16^m$, $\delta = -69°15'$). The procedure has been to take alternating red and blue images with 8-minute exposures for the red and 12-minute exposures for the blue. The read-out time of one exposure is 40 seconds (all the CCDs are read in parallel). As of March 1993, a total of 8,100 exposures has been taken. Figure 5 shows the number of exposures per week over the 1992–93 season. In 1993, the observing efficiency reached 70 per cent for all nights and 85 per cent for useful nights.

3. The Photographic Plate Programme

Over the period 1990–1993, a total of 308 Schmidt plates of the LMC has been taken for our programme at La Silla, Chile. Figure 6 shows the time distribution of the plates. Half the plates use a red filter (RG630) and 098-04 emulsion and half a blue filter (GG385) and IIaO emulsion. Exposure times were typically 1 hour, allowing us to monitor stars of twentieth magnitude in the red and blue. The field covers 5 × 5 degrees and is centred on ($\alpha = 5^h20^m$, $\delta = -68°30'$).

The transparency of the plates is digitized in 10 μm (0.6 arcsec) steps by the "MAMA" (Machine Automatique à Mesurer pour l'Astronomie [7]) at the Observatoire de Paris. Digitization of one plate requires about 8 hours time on the MAMA and generates 1.6 gigabytes stored on ten 3,480 magnetic tapes. As of this writing, all but 40 plates have been digitized.

4. Data Analysis

The analysis of such a large quantity of data taken under varying conditions presents considerable programming challenges. The use of standard photometric programmes has not proved feasible because of computer time limitations. After two years of development, we are now satisfied that we have an analysis package that can treat the entity of these data in a reasonable time. We describe successively the procedure for the analysis of CCD images and Schmidt plates.

To analyse the CCD images, we first construct one reference image for each CCD and for each colour by combining 50 images taken with good atmospheric conditions. The reference image is subjected to a star finding algorithm, and a star catalogue is established, containing about 10,000 stars per CCD.

In a second step, the individual images are treated as follows. After deflatting and bias subtraction, an image is aligned with the reference image. The positions of the stars previously found on the reference image serve as input to a photometric fitting programme to determine the luminosity of each catalogue star on the new image. The photometric precision is typically 6 per cent. The image is then aligned "photometrically" with the reference image by requiring that the mean luminosity of stars in a given luminosity band be equal to the mean luminosity in the catalogue. (The small number of intrinsically variable stars in the catalogue does not affect this procedure.) Successive images then add one point to the blue or red light curve of each star in the catalogue.

The light curve of one variable star is shown in Figure 7.

The final step of the analysis is to test each light curve for the presence of a microlensing event. Because the event finding algorithms must reject random fluctuations of intrinsically stable stars due to measurement errors, it is essential to determine accurately the photometric precision for each star and for each image. This precision is a function of the star's magnitude, its environment, and the observing conditions. We determine the "nominal" precision for each star from the mean point to point variations on the light curves using only the points from 50 high quality images. For intrinsically variable stars, this procedure yields an estimated precision that is worse than the real precision. However, it accurately estimates the mean

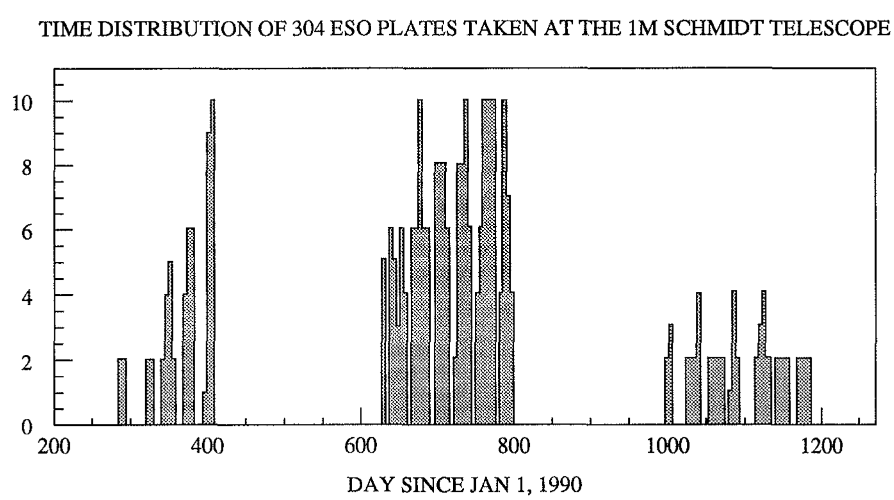


Figure 6: *Number of Schmidt plates per five days (1990 to 1993).*

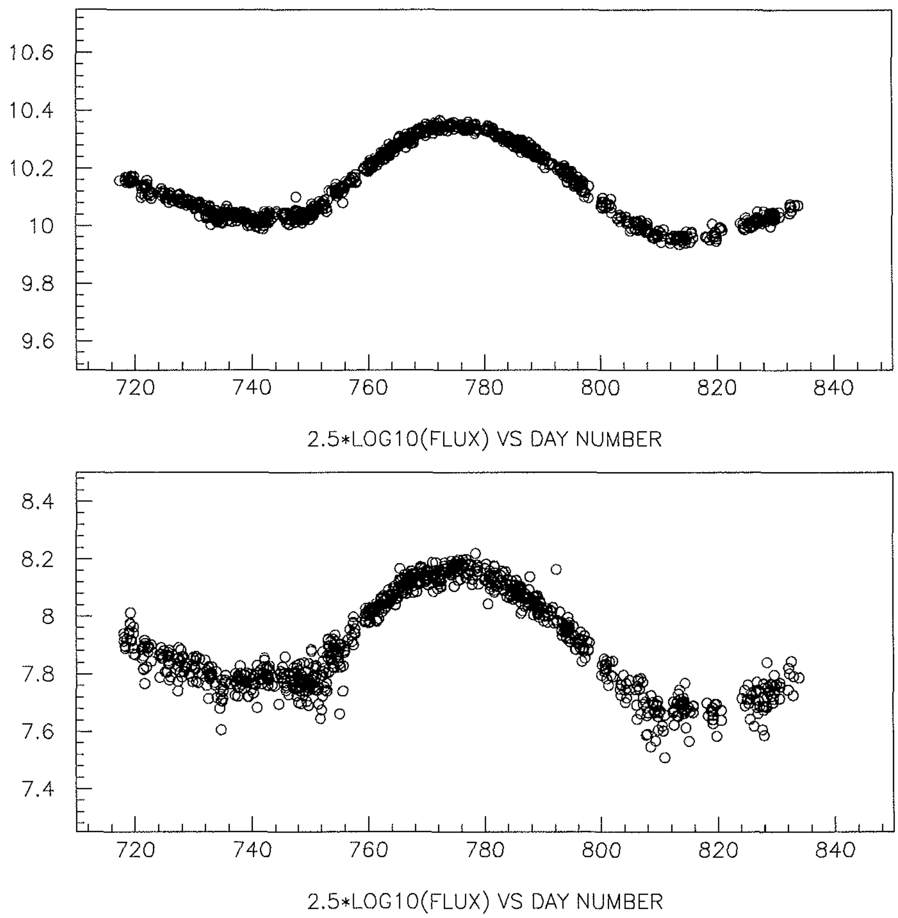


Figure 7: *A variable star observed with the CCD system in the 1991–92 season. The red (up) and blue (down) light curves contain about one thousand measurements each. Days are counted since January 1, 1990.*

precision for stable stars. A given point on the light curve is then assigned an uncertainty equal to the star's nominal precision multiplied by a factor that takes into account the quality of the image.

Once the resolution for each star and image is determined, algorithms can be applied to the light curves to search for microlensing candidates. The algorithm should accept light curves exhibiting one *and only one* amplification that is greater than that expected from measurement errors. Additionally, the amplifications in the two colours should be equal within errors and the temporal development of the amplification consistent with the expected curve. After application of the algorithm to the set of light curves, the number of events accepted by the algorithm can then be compared with the number expected if the Halo is comprised of astronomical objects of a given mass distribution. This number must be estimated via a Monte Carlo simulation of the observation sequence and detector resolution. The number will depend on the distribution of deflector masses and, to a lesser extent, on the spatial distribution of deflectors in the Halo.

We have investigated several possible algorithms for identifying microlensing events from the observed red and blue light curves. Basically we scan the two light curves for sequences of consecutive points that exhibit a mean luminosity sufficiently superior to that of the reference image. Candidates are chosen if they exhibit one and only one such sequence. These candidates are then examined in detail to verify that their light curves are compatible with the characteristics expected for microlensings.

As of this writing, the entire analysis chain has been applied to the 1991–92 data for two CCDs; this corresponds to five per cent of the total data. We have found *no candidates* that satisfy all criteria. For this quantity of analysed data, *we expect about 0.5 candidates* if the Halo is comprised of dark objects in the range 10^{-7} to 10^{-4} solar masses. This number of events is nearly independent of deflector mass in this range because the rising detection efficiency is compensated by the falling total number of microlensing events.

At the current analysis rate, we expect to treat all presently available data within a year. This will result in about ten candidates if the Halo objects are indeed in the above mass range.

The analysis of the Schmidt plates proceeds through basically the same steps as in the CCD programme. The plates are divided into 784 1-cm^2 blocks (10^6 pixels per block) that are treated separately. A reference image for each block and for each colour is constructed by combining ten images. A catalogue of about 10,000 stars on an average is constructed in each block, which then serves as input to the photometric reconstruction programmes for individual images. The mean stellar luminosity corresponds to 19^{th} magnitude.

The mean photometric precision determined from the point-to-point variations on the light curves is about 15 per cent for the 50 % brightest stars. The linearity of the photometric algorithms is confirmed using photometric sequences taken by us with the Danish 1.5-m telescope in fields scattered throughout the LMC.

The light curve from one variable star is shown in Figure 8. The light curve from a simulated microlensing event is shown in Figure 9.

The photometric analysis for the present data will require 3,000 cpu hours on a large IBM computer. As of this writing, ten per cent of the total field has been treated for the 1990–91 and 1991–92 data. At the current rate, the totality of the available data can be treated in about a year's time.

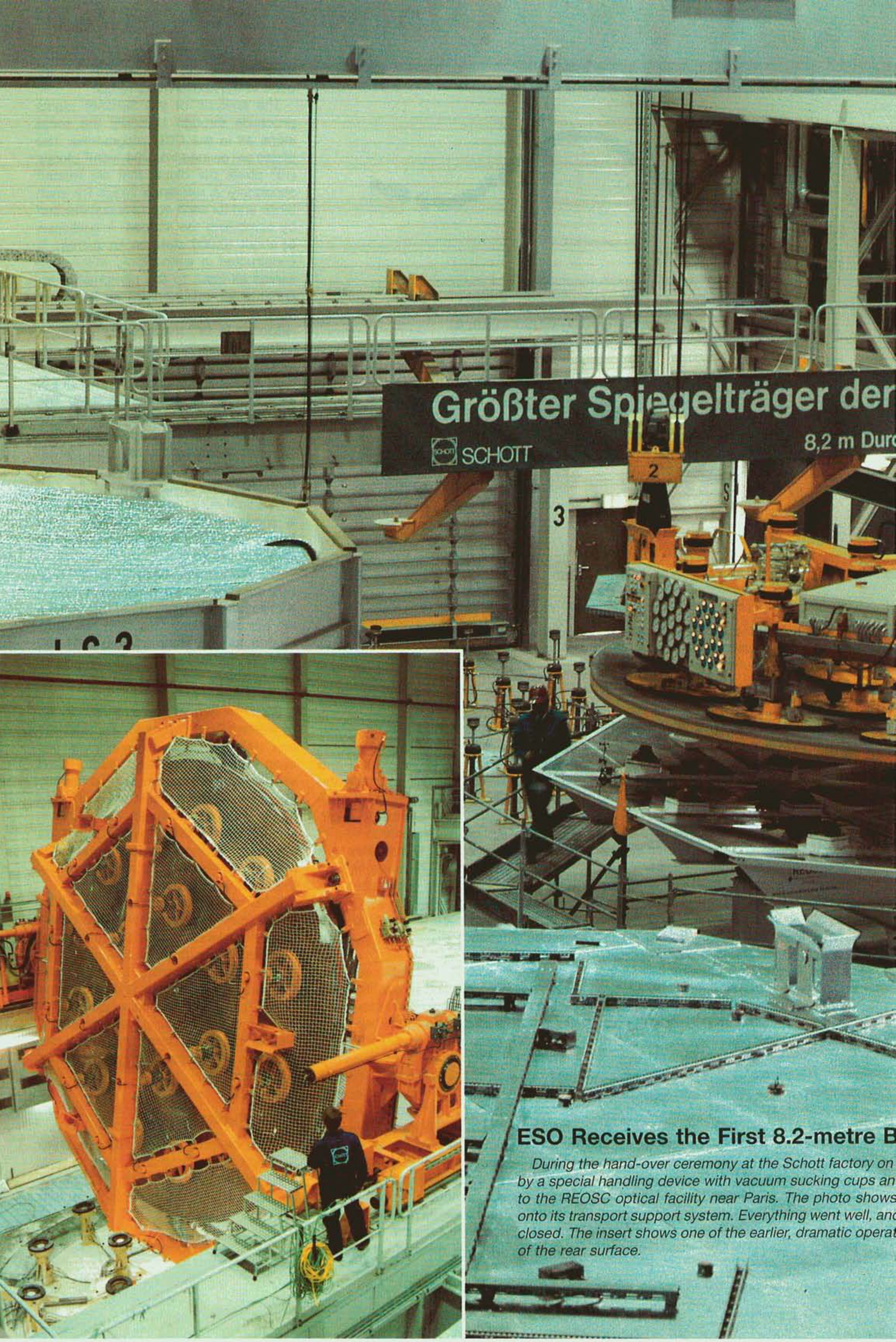
Selection algorithms have been tuned by treating three blocks for the 1990–91 and 1991–92 data. (No candidate has been found, for 0.07 expected). Based on this analysis, we expect to identify about twenty microlensing events when all the data are analysed, if the Halo is indeed comprised of objects of masses betweeen 10^{-4} and one solar mass. We also expect to identify more than ten thousand variable stars.

In conclusion we remark that we now know, from the absence of any candidate microlensing event in the data analysed so far, that the background of variable stars simulating a microlensing is small, both for the CCD data and the Schmidt plates. It is even small enough that each microlensing candidate that we may find can be scrutinized at the raw data level, and submitted to other algorithms.

5. The Future

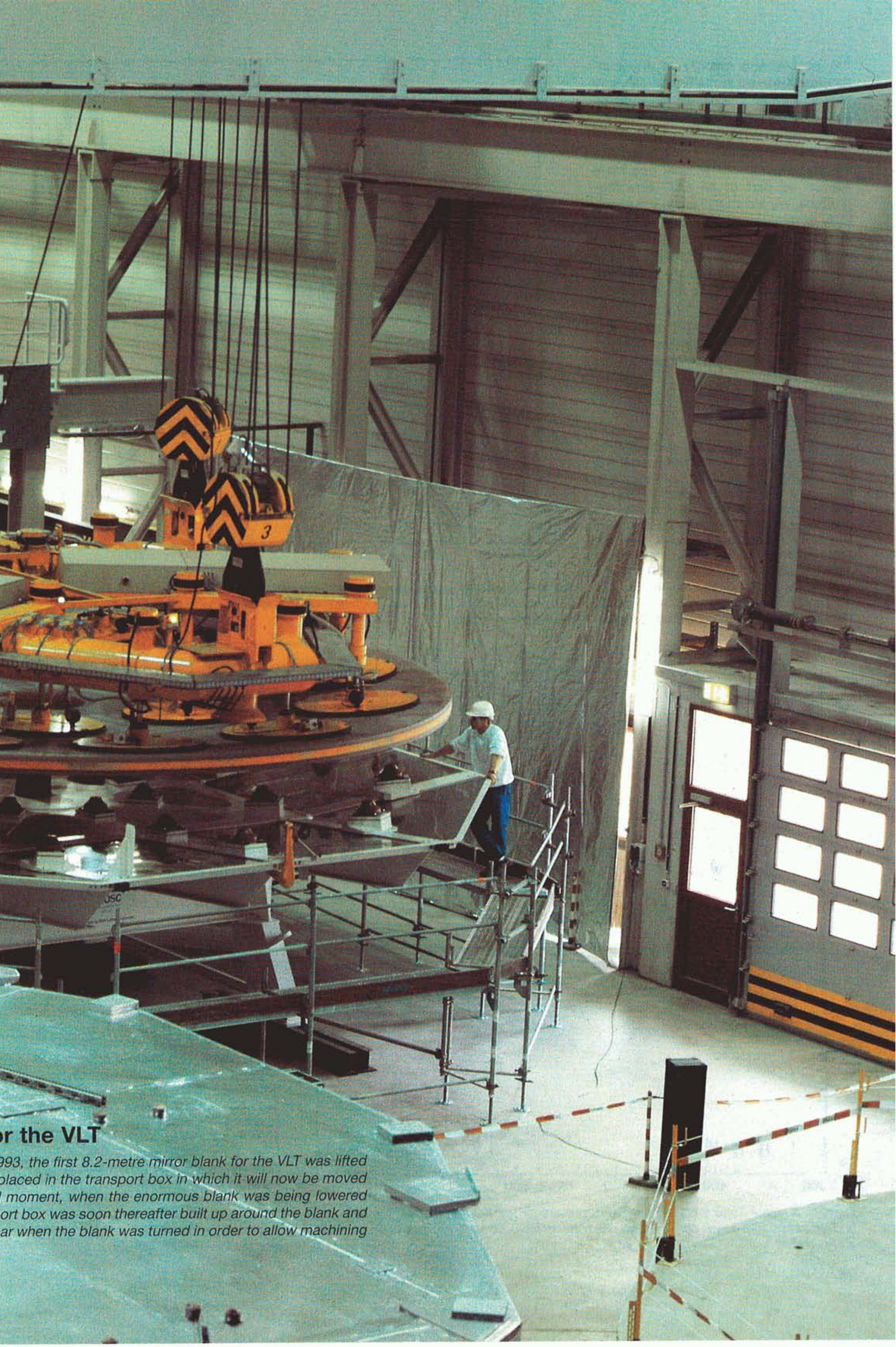
We have proposed to continue the Schmidt plate programme for a few years at the rhythm of about 50 plates per season. This will allow us to confirm

(continued on page 26)



ESO Receives the First 8.2-metre B

During the hand-over ceremony at the Schott factory on
by a special handling device with vacuum sucking cups an
to the REOSC optical facility near Paris. The photo shows
onto its transport support system. Everything went well, and
closed. The insert shows one of the earlier, dramatic operat
of the rear surface.



or the VLT

993, the first 8.2-metre mirror blank for the VLT was lifted placed in the transport box in which it will now be moved l moment, when the enormous blank was being lowered ort box was soon thereafter built up around the blank and ar when the blank was turned in order to allow machining the post-lensing stability of any candidates observed in the first three years and to further search for lensings on very long time scales.

We plan to continue the observations with the present CCD camera and the 40-cm telescope for at least one more season as part of an ESO Key Programme. We are investigating the possibility of replacing the present telescope in 1995 with a 1-metre-class telescope equipped with a larger CCD camera. For the long term, some of us are involved in the LITE proposal [8] to build a wide-field 2-metre telescope for the Paranal site. Searches for microlensings with such a telescope are expected to result in ten times more candidates than the present system.

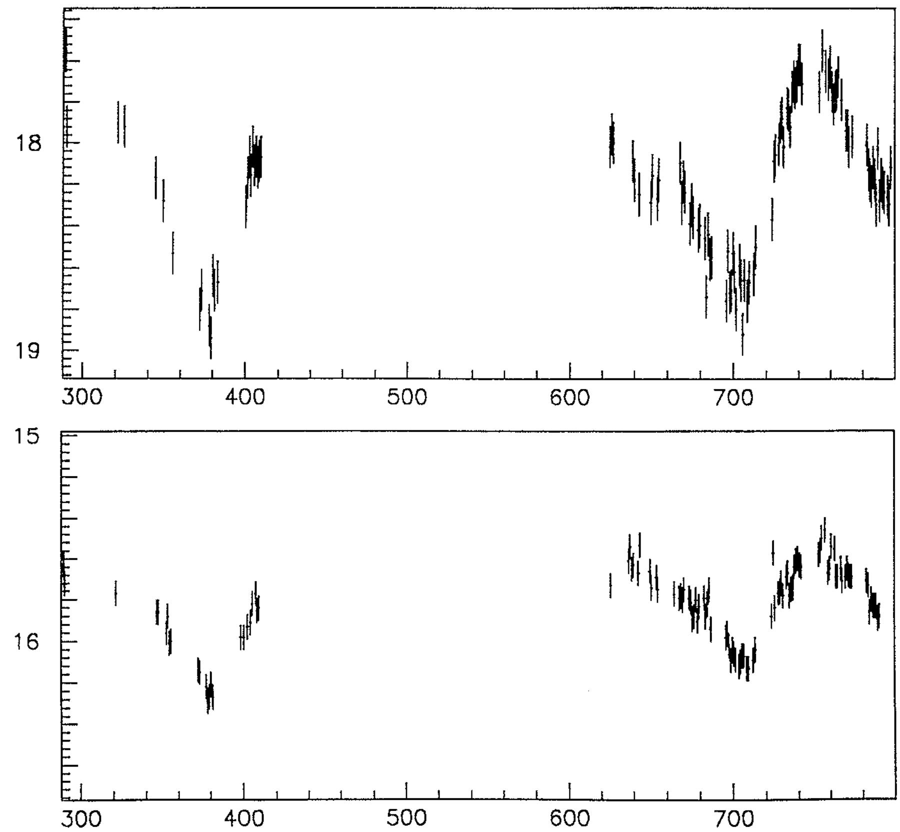


Figure 8: *A variable star found on the Schmidt plates using the 1990–92 data. The blue (up) and red (down) light curves contain about one hundred measurements each. Days are counted since January 1, 1990.*

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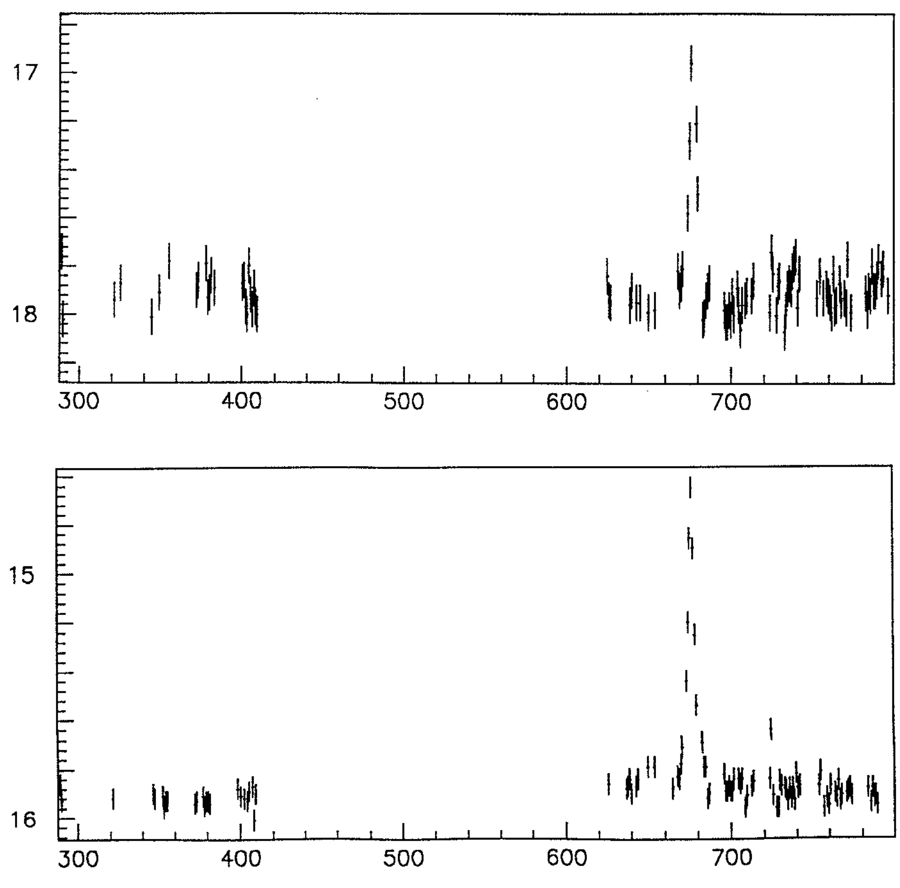

Figure 9: *A Monte-Carlo simulated microlensing event for the 1990–92 period. The blue (up) and red (down) light curves contain about one hundred measurements each. Days are counted since January 1, 1990.*

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First Optical Identification of an Extragalactic Pulsar

The recent identification of the optical image of a pulsar in the Large Magellanic Cloud is a fine illustration of astronomy as a high-tech international science. It is the first extragalactic pulsar to be so identified and only the third radio pulsar, after those in the Crab and Vela nebulae in the Milky Way, for which this has been possible.

The conclusive observations were made in early 1993 by astronomers from Ireland, Denmark and ESO[1] with TRIFFID[2], a new, powerful instrument of their own design, used together with the ESO MAMA[3] detector system and attached to the 3.5-metre New Technology Telescope (NTT) at the ESO La Silla observatory in Chile. Earlier observations by Italian astronomers with the same telescope were crucial for the success of this research project.

A Spinning Neutron Star in the Large Magellanic Cloud

The Large Magellanic Cloud (LMC), a satellite galaxy to the Milky Way galaxy in which we live, is one of the most studied objects in the sky. In addition to several millions of stars it also contains a great number of nebulae of gas and dust. Some of these have been found to be the remains of gigantic supernova explosions in the past when heavy stars in the LMC became unstable and blew up. The most recent happened as late as in February 1987, when Supernova 1987A became the first naked-eye supernova in 400 years.

One of these nebulae has a circular shape with a diameter of about 6 arcseconds; it is believed to be the remnants of the penultimate LMC supernova which exploded some 760 $\pm$ 50 years ago; this age is deduced from the expansion rate of the nebula. In 1984, a group of American astronomers studied the data from the Einstein X-ray satellite observatory and found that pulsed X-rays are emitted from the direction of this nebula. The measured pulsation frequency is unusually high and has now been refined to 19.838 Hz (pulses per second).

This is explained by the presence of a pulsar somewhere inside the nebula, that is an extremely compact neutron star which weighs as much as the Sun, but has a diameter of 10–15 kilometres only. It was created by enormous pressures during the supernova explosion. The observed pulses indicate that it is now spinning around its axis once every 0.05 seconds. The nebula in which it is imbedded contains the rest of the material that was thrown out during the explosion.

The new object received the designation PSR 0540-693 (the numbers indicate its approximate position in the sky). Because of its many similarities with the Crab pulsar and nebula, it has also been nicknamed the Crab Twin.

Due to the large distance to the LMC, of the order of 160,000 light-years, it has not been possible, until recently, to measure the very faint radio emission from this pulsar with southern radio telescopes. The X-ray observations only fix the pulsar position within a circle with a diameter of about 4 arcseconds (the "X-ray error circle"), and since detailed radio observations cannot be made of this faint radio source, it is impossible to determine the position of PSR 0540-693 with sufficient accuracy to permit identification of its optical image. Variations of the optical emission with the above X-ray frequency were measured in the mid-1980's from the general area of the nebula, but the image sharpness achievable with the astronomical telescopes available at the time did not allow the detection of a star-like object inside the relatively bright nebula.

Narrowing Down the Choice

This was the situation in early 1992 when a group of Italian astronomers[4] obtained images of the field around PSR 0540-693 with the ESO NTT.

Thanks to excellent weather conditions, the remarkable optical quality of the NTT and the fine performance of the ESO SUSI high-resolution CCD camera, they were able to record the most detailed images ever made of this region. Although the comparatively strong light from the nebula tends to "wash out" any details within its confines, they detected for the first time the presence of two star-like objects inside the nebula. Both were much fainter than the nebula itself; they are located in the south-west area of the nebula (near the edge of the X-ray error circle) and are separated by about 1.3 arcseconds. (See the photo on page 28).

Because all of the exposures necessarily lasted much longer than the 0.05 second pulse interval, these observations did not permit to decide if any of the two had a variable light intensity and might therefore be the pulsar. Still, when the Italian astronomers published their new results[5], they remarked that the northernmost of the two objects was more likely to be the pulsar; this image was somewhat more star-like (sharper) than the other one and a jet-like symmetrical structure appeared to be exactly centered on it.

[1] The group consists of Andy Shaerer, Mike Redfern and Peter O'Kane from the University College Galway (Ireland), Holger Pedersen from the Copenhagen University Observatory (Denmark) and Martin Cullum from ESO.

[2] TRIFFID = TRansputer Instrument For Fast Image Deconvolution. This image sharpening camera was built by the University College Galway in collaboration with the Dunsink Observatory of the Dublin Institute for Advanced Studies (DIAS). The construction of TRIFFID and the observational programme which lead to the identification of the pulsar were funded by EOLAS, the Irish Science & Technology Agency.

[3] MAMA = Multi-Anode Microchannel Array.

[4] This group consisted of Patrizia Caraveo, Giovanni Bignami, Sandro Mereghetti from the Istituto di Fisica Cosmica del CNR and Marco Mombelli from the Dipartimento di Fisica, Università degli Studi, Milan, Italy.

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New ESO Publications

SCIENTIFIC REPORT No. 12: "Second Catalogue of Stars Measured in the Long-Term Photometry of Variables Project (1986–1990).

OPERATING MANUAL No. 17: "Remote Control of the 3.5 m New Technology Telescope at the European Southern Observatory – User Guide."