BARYONIC DARK MATTER

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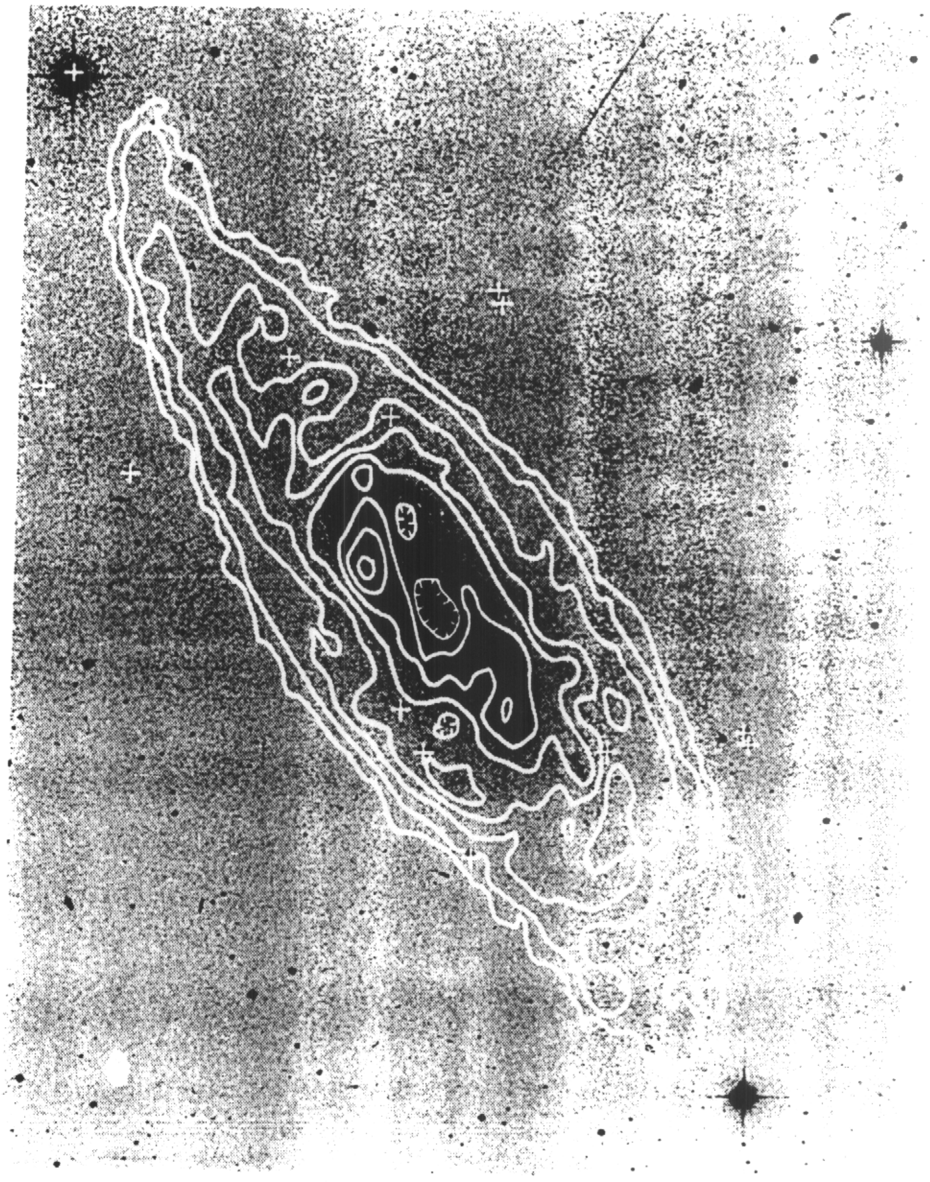
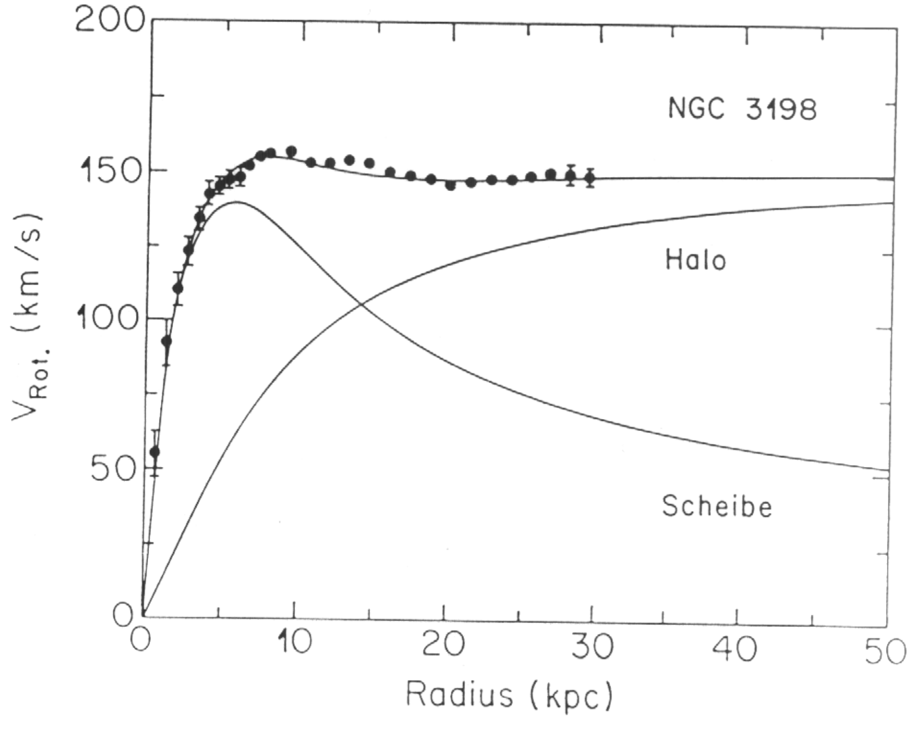




NGC 3198
Halo
Scheibe
200
150
100
50
0
V_Rot. (km/s)
0
10
20
30
40
50
Radius (kpc)

Dark matter in spiral galaxies

From (Doppler shift) measurementes of the rotation curve it follows that:

$v_{rot} \simeq$ constant

rather than to fall as $v_{rot} \sim \frac{1}{\sqrt{r}}$ in the outer regions, where there are no longer stars.

$\Rightarrow$ presence of dark matter

There is evidence for dark matter also in elliptical galaxies and in clusters of galaxies.

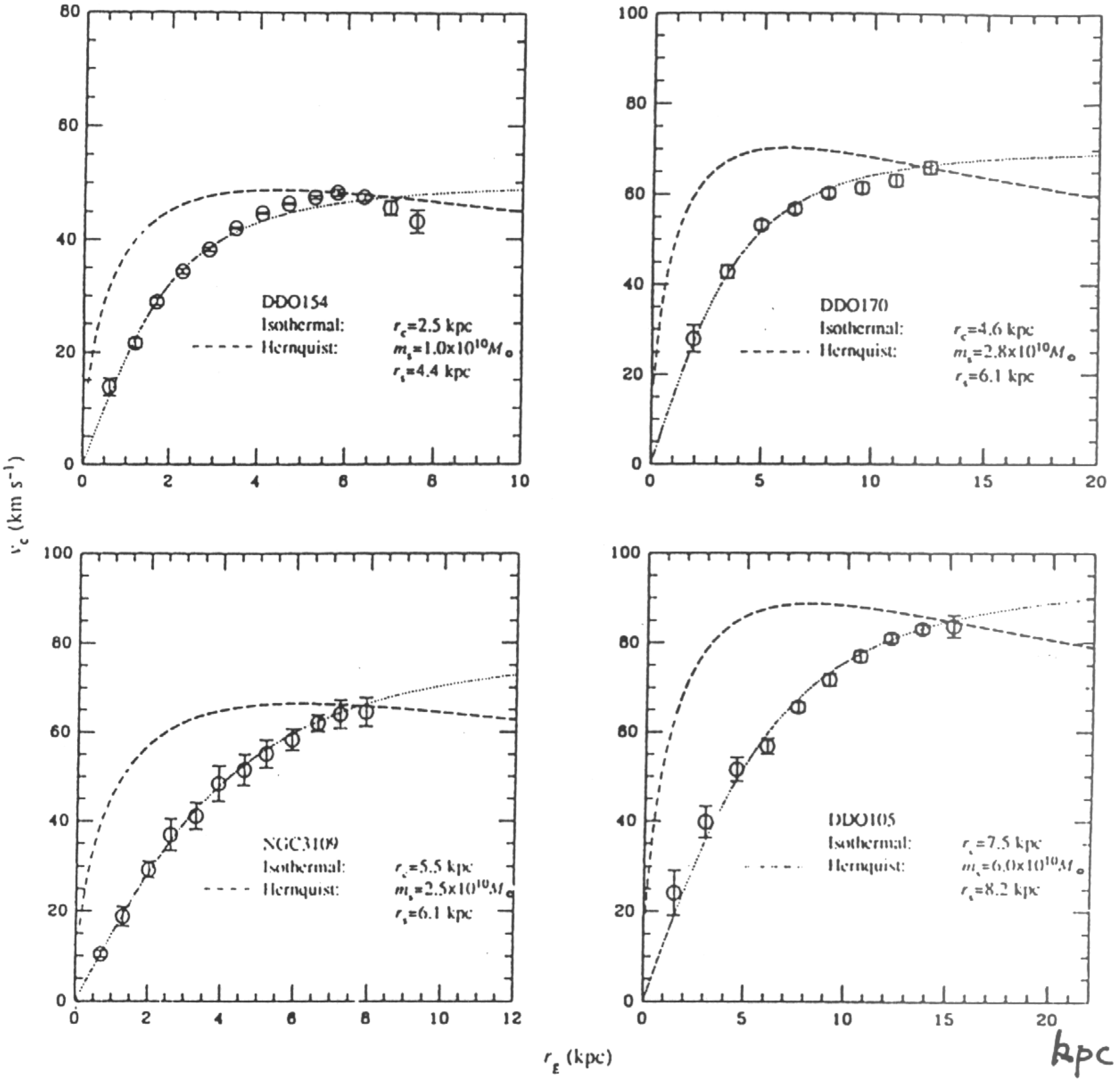
Dark matter in spiral galaxies

There is indirect evidence that the halo might be extended up to 200 kpc.

Total mass:

$$M_{tot} > 1.4 \times 10^{12} M_{\odot}$$
$$\sim 6 \times 10^{12} M_{\odot}$$

Luminous matter $\sim 7 \times 10^{10} M_{\odot}$
(up to LMC $\sim$ **50 kpc:** $\sim 5 \times 10^{11} M_{\odot}$).



\- - - CDM rotation curve (calculated)

. . . . . observed rotation curve (interpolation)

Possible baryonic candidates

- Massive black holes * ($> 100\ M_\odot$)
- Neutron stars *
- White dwarfs *
- Brown dwarfs or M-stars *

  ($M_{BD} \leq 0.08 M_\odot$)
- Cold H_2 clouds

(Ionized H makes up at most 5% of dark matter in the halo, see e.g. F. De Paolis, G. Ingrosso, Ph. J., M. Roncadelli, Astron. & Astrophys. 329, 74 (1998))

Possible baryonic candidates

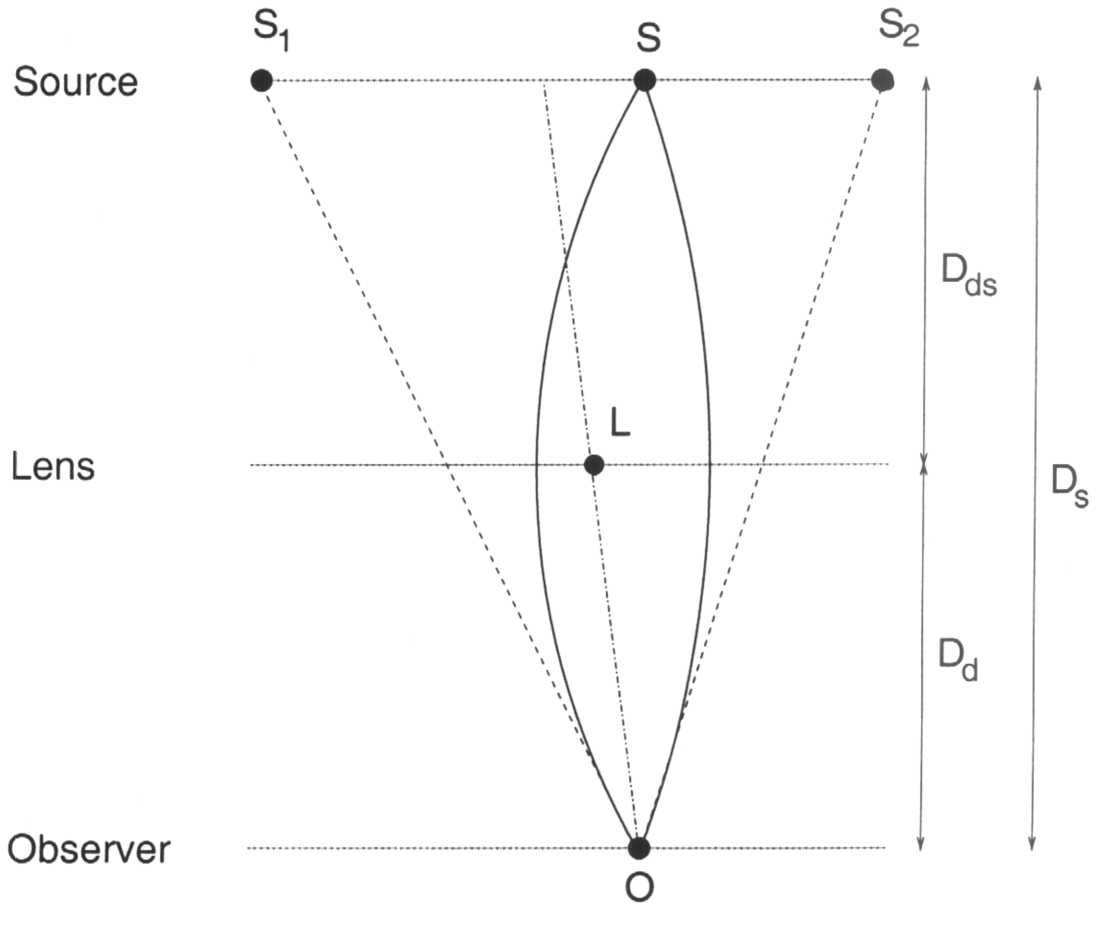
* also called [redacted]:

- [redacted]assive
- [redacted]strophysical
- [redacted]ompact
- [redacted]alo
- [redacted]bjects

Gravitational microlensing

(B. Paczyński, ApJ **304**, 1 (1986))

Principle: general relativistic light deflection and magnification



Setup of a gravitational lens situation: The lens L located between source S and observer O produces two images S_1 and S_2 of the background source. D_d is the distance between the observer and the lens, D_s between the observer and the source and D_{ds} between the lens and the source.

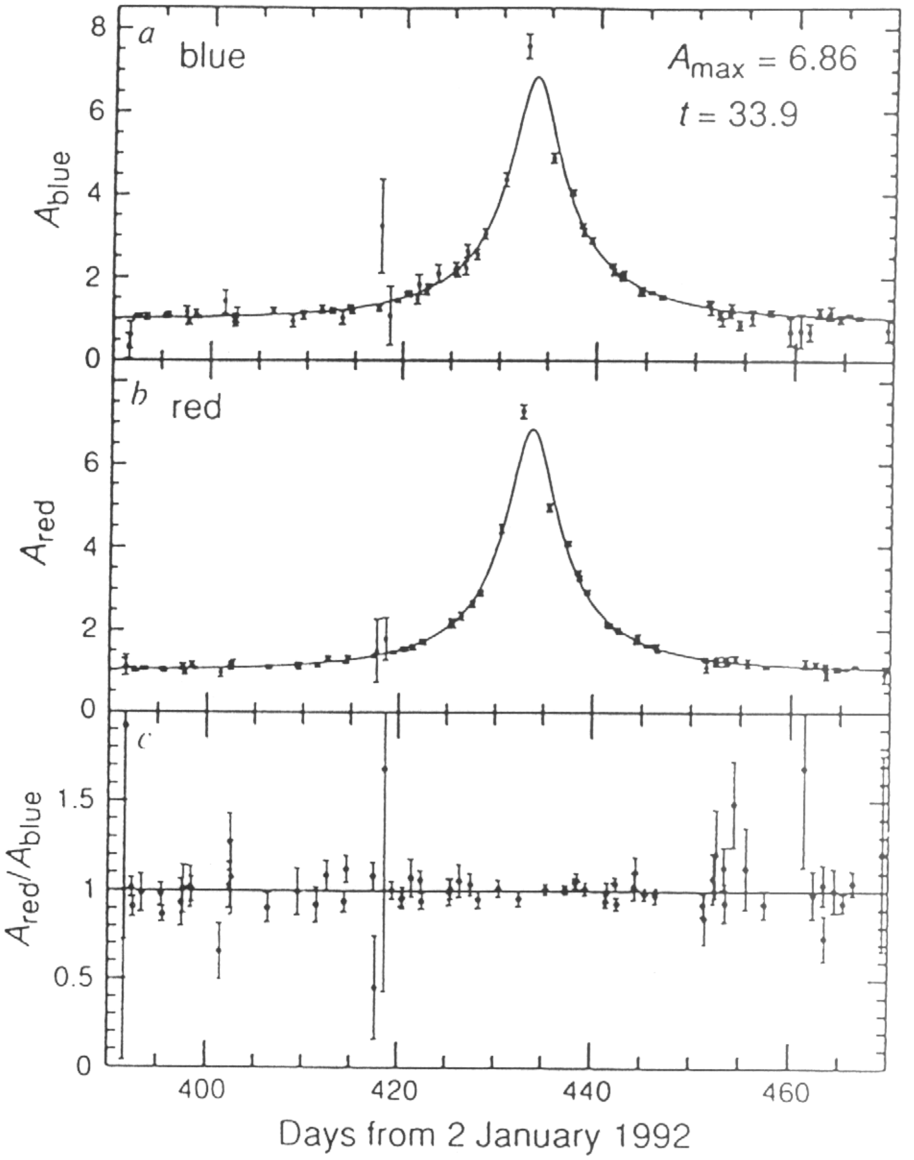


FIG. 2 As in Fig. 1, with an expanded scale around the candidate event. The smooth curve shows the best-fit theoretical microlensing model, fitted simultaneously to both c is the colour light curve, showing the ratio of red to blue flux, normalized so that the median is unity.

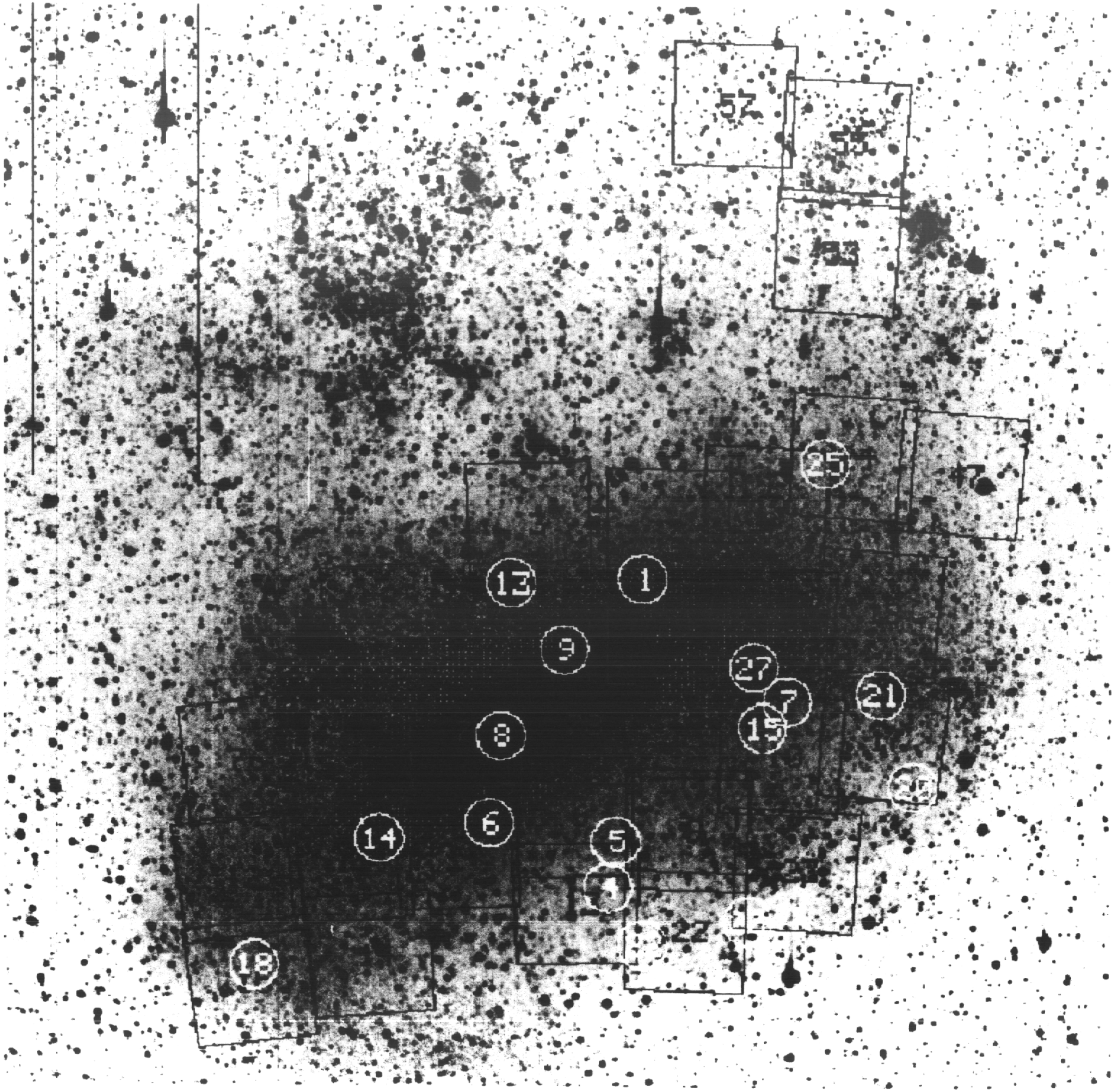
Since the discovery of the first microlensing events in 1993 more than 300 events have been discovered:

LMC $\sim$ 20 events (EROS + MACHO)

SMC $\sim$ 2 events

Galactic bulge region $\sim$ 300 events

Spiral arms $\sim$ 10 events


57
55
53
25
47
13
1
9
27
7
21
15
8
6
14
5
22
18

Analysis of the 13 - 17 events found during 6 years of observation by the MACHO collaboration leads to:

$$\tau = 1.2^{+0.4}_{-0.3} \times 10^{-7}$$

$$f \simeq 20\% \qquad (8 - 50\%)$$

Mass in the range: $\sim 0.1 - 0.9 M_\odot$ depending on the adopted halo model

(spherically symmetric model: $\sim 0.5 M_\odot$)

Optical depth τ

τ = probability that at any instant of time a given star is within the angle $\theta_E = \frac{R_E}{D_d}$ of a lens (MACHO).

Consider the following spatial distribution of dark matter in the halo

$$\rho(\vec{r}) = \rho_\odot \, \frac{a^2 + R^2}{a^2 + \vec{r}^2} \tag{5}$$

where

$R \simeq 8.5$ kpc distance of the Sun from the galactic center

$a \simeq 5.6$ kpc "core" radius

$| \vec{r} |$ distance of MACHO from galactic center

$\rho_\odot \simeq 0.3$ GeV/cm^3 $\simeq 10^{-2}$ $M_\odot$/pc^3 is the dark matter density in solar neighbourhood

Optical depth τ

$$\tau = \int_0^{D_s} \frac{4\pi G\rho}{c^2} \frac{D_d D_{ds}}{D_s} \, dD_d$$

$$= \frac{4\pi G}{c^2} \int_0^1 \rho(x) \; x(1-x) \; dx \qquad (6)$$

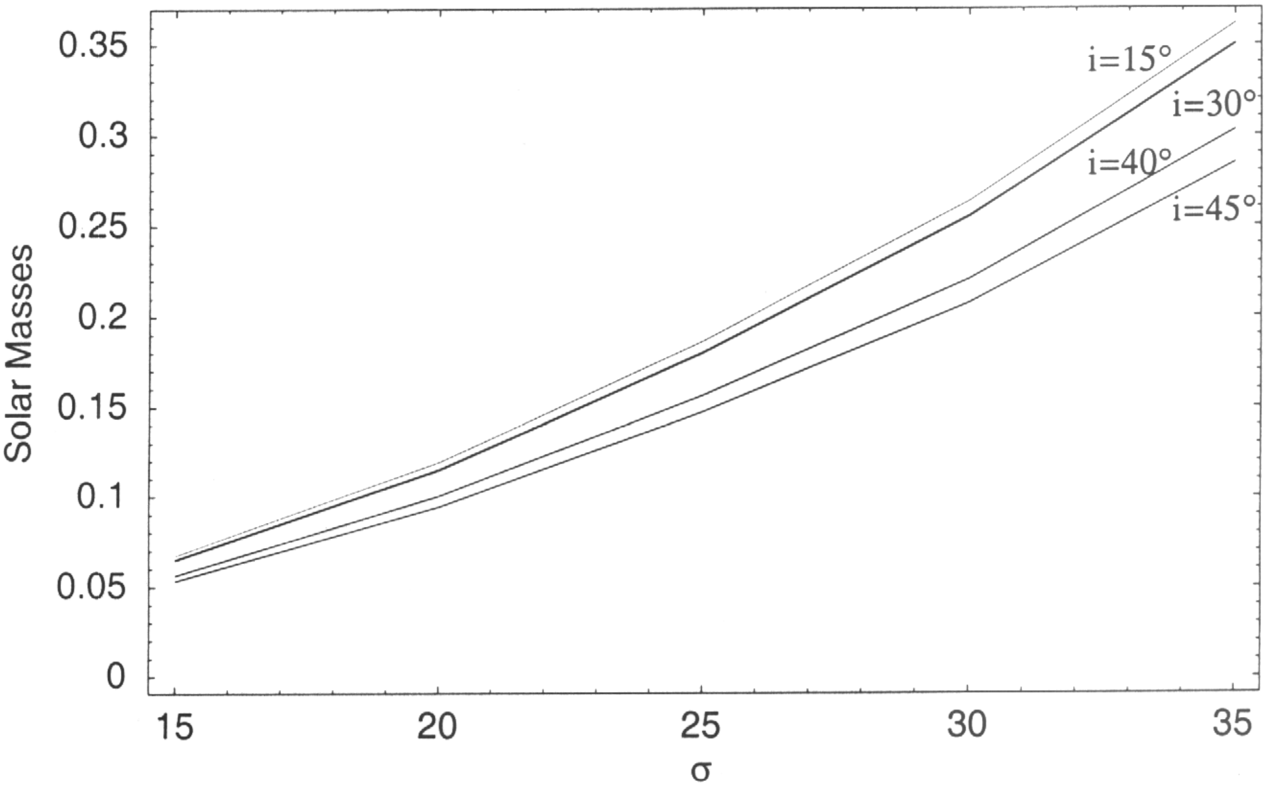
where $x = D_d/D_s$. ("Integration" of ρ along the line of sight).

$\tau \simeq 5 \times 10^{-7}$ for LMC or SMC stars

need to observe $\sim 10^6$ stars

Expected number of events (for MACHO 6 years observations):

3 - 4 events



Variation of the mean mass, as a function of the velocity dispersion σ, with the LMC disk inclination, in the case of self-lensing.

(Ph. J., L. Mancini, G. Scarpetta, 2001 submitted)

Source/Lens Geometry	*Relative Weight*	τ $(a) - (b)$
Disk/disk	0.53	$(1.34 - 2.23) \times 10^{-8}$
Disk/bar	0.53	$(0.80 - 1.33) \times 10^{-8}$
Bar/disk	0.47	$(1.07 - 1.78) \times 10^{-8}$
Bar/bar	0.47	$(1.33 - 2.21) \times 10^{-8}$
Total	1	$(2.26 - 3.77) \times 10^{-8}$

Theoretical estimates of the optical depth towards LMC, averaged over 27 MACHO fields, for different source/lens geometries in the case of self-lensing, with our preferred values for the parameters and for a *LMC* mass in the range between (a) $3 \times 10^9\, M_\odot$ and (b) $5 \times 10^9\, M_\odot$.

Direct detection of a microlens in the Milky Way

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The nature of dark matter remains mysterious, with luminous material accounting for at most ~25 per cent of the baryons in the Universe[1,2]. We accordingly undertook a survey looking for the microlensing of stars in the Large Magellanic Cloud (LMC) to determine the fraction of Galactic dark matter contained in massive compact halo objects (MACHOs). The presence of the dark matter would be revealed by gravitational lensing of the light from an LMC star as the foreground dark matter moves across the line of sight. The duration of the lensing event is the key observable parameter, but gives non-unique solutions when attempting to estimate the mass, distance and transverse velocity of the lens. The survey results to date indicate that between 8 and 50 per cent of the baryonic mass of the Galactic halo is in the form of MACHOs (ref. 3), but removing the degeneracy by identifying a lensing object would tighten the constraints on the mass in MACHOs. Here we report a direct image of a microlens, revealing it to be a nearby low-mass star in the disk of the Milky Way. This is consistent with the expected frequency of nearby stars acting as lenses, and demonstrates a direct determination of a lens mass from a microlensing event. Complete solutions such as this for halo microlensing events will probe directly the nature of the MACHOs.

The MACHO project has reported[3,4] microlensing events in the LMC. We have now performed follow-up observations, obtaining images (from the Hubble Space Telescope, HST, Wide Field Planetary Camera 2) of fields containing the source stars of many of these microlensing events. A Planetary Camera image of the LMC-5 system was taken on 13 May 1999 with total exposure times of 1,600 s, 800 s and 1,000 s in the F555W (V), F675 (R) and F814W (I) bands. This image was taken 6.3 years after the peak of the microlensing event on 5 February 1993. The pixel size of the Planetary Camera (0.046″) was sufficient to resolve the microlensing system, and show it to be composed of a faint, red object displaced by 0.134″ from the centre of an LMC main-sequence star that, on the basis of previous analysis[4], is the source star of this event (Fig. 1a). Further analysis of the HST data, described here, combined with the results of a fit to the microlensing light curve suggests that the faint, red object is the lens (Fig. 1b). This is consistent with previous suggestions[5,6] that this event is the result of lensing by a faint Milky Way star. We note that the detection of one such event in our current sample of 13–18 events is completely consistent with the expected number of Milky Way events[3] associated with known populations. We have completed HST analysis of 17 of these events, and find no other plausible candidates for lensing by Milky Way stars.

The chance placement of the source star near a foreground object in our image is very low. The density of stars with V-band magnitude $V < 26$ in the LMC-5 frame is $\rho = 1.8 \times 10^{-3}$ per pixel^2. The frequency of red objects with $V < 26$ and $(V - I) > 2.6$ in all our LMC Planetary Camera image[4] is 8.8×10^{-4}. Thus the chance superposition of a red object within 0.5″ of the source star is about 1 in 10,000. Therefore, we assume that

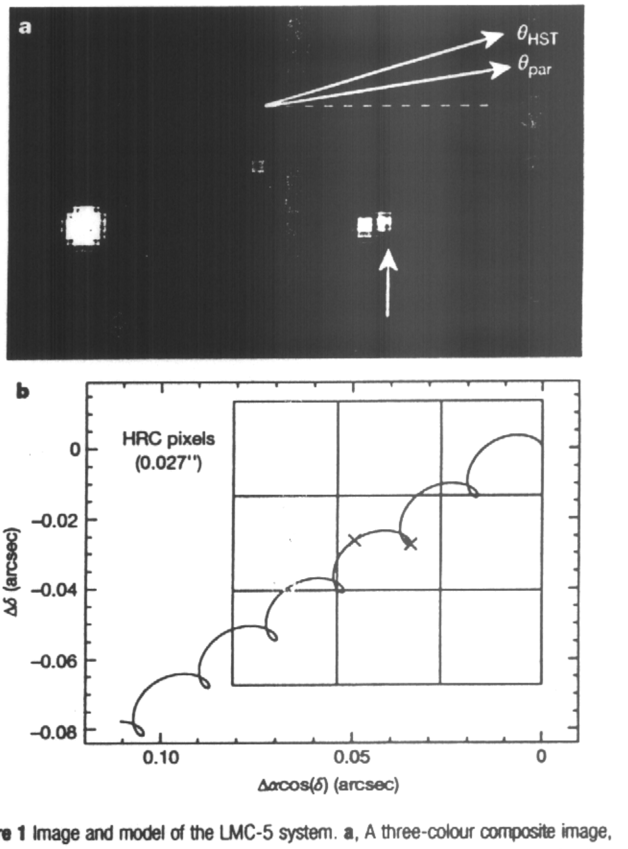


Figure 1 Image and model of the LMC-5 system. **a**, A three-colour composite image, made up of the WFPC2 V-, R- and I-band images of LMC-5 obtained by the HST. The microlensing source star is the blue star near the centre of the figure, which is partially blended with a much redder object (indicated by the arrow) displaced by 0.134″. The direction of motion of the lens on the sky derived from the HST ($\theta_{HST} = -92°$) and unconstrained parallax fit ($\theta_{par} = -100°$) are both shown. **b**, The lens motion on the plane of the sky includes both the physical motion through space (proper motion) and an apparent small elliptical contribution due to the Earth's orbit around the Sun (parallax motion). The motion is plotted in equatorial coordinates in terms of right ascension, α, and declination, δ. At a distance of 200 pc, the parallax contribution has a diameter of 0.01″. The overlaid grid shows the pixel size of the high resolution channel of the HST Advanced Camera for Surveys. Future measurements with this instrument may allow direct measurement of the lens parallax.

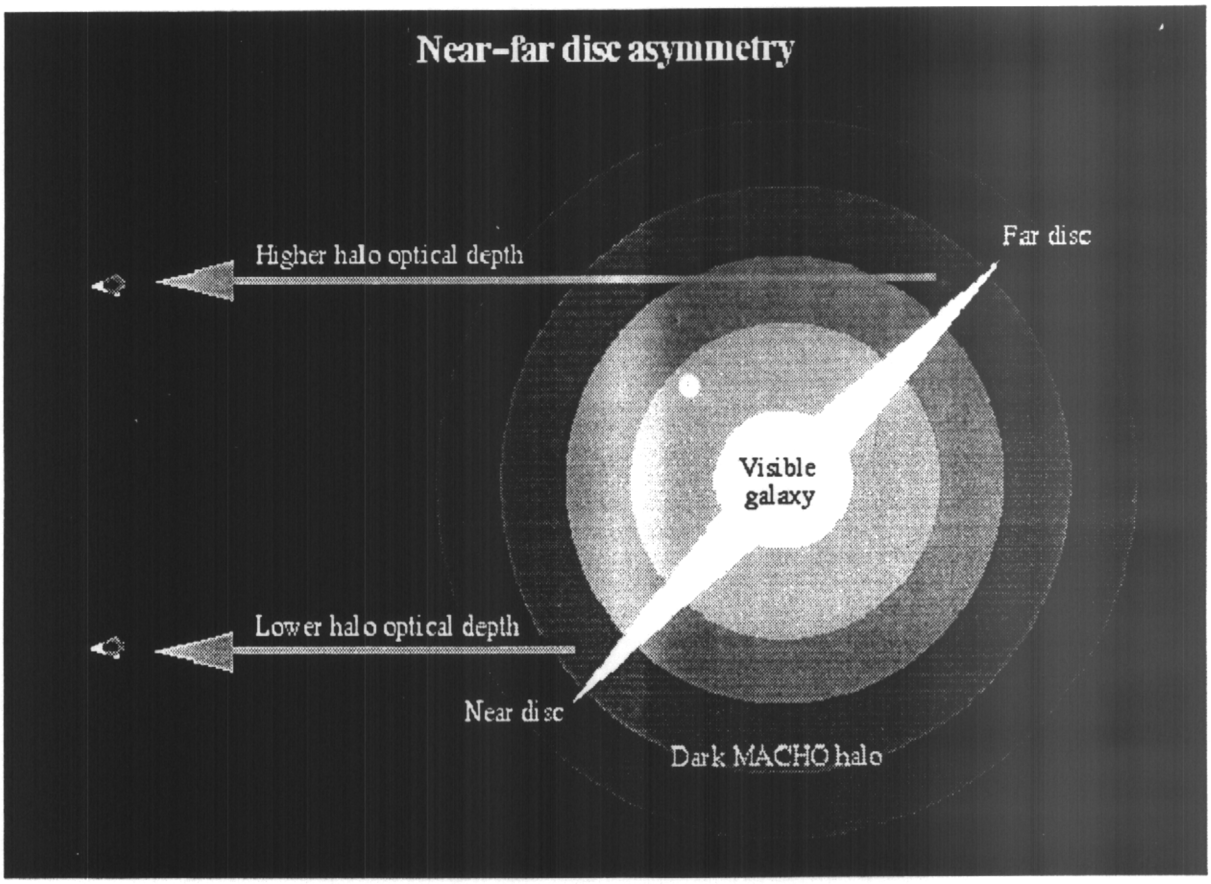
Eamonn Kerins
(Oxford)

Uncovering Andromeda's MACHO Image

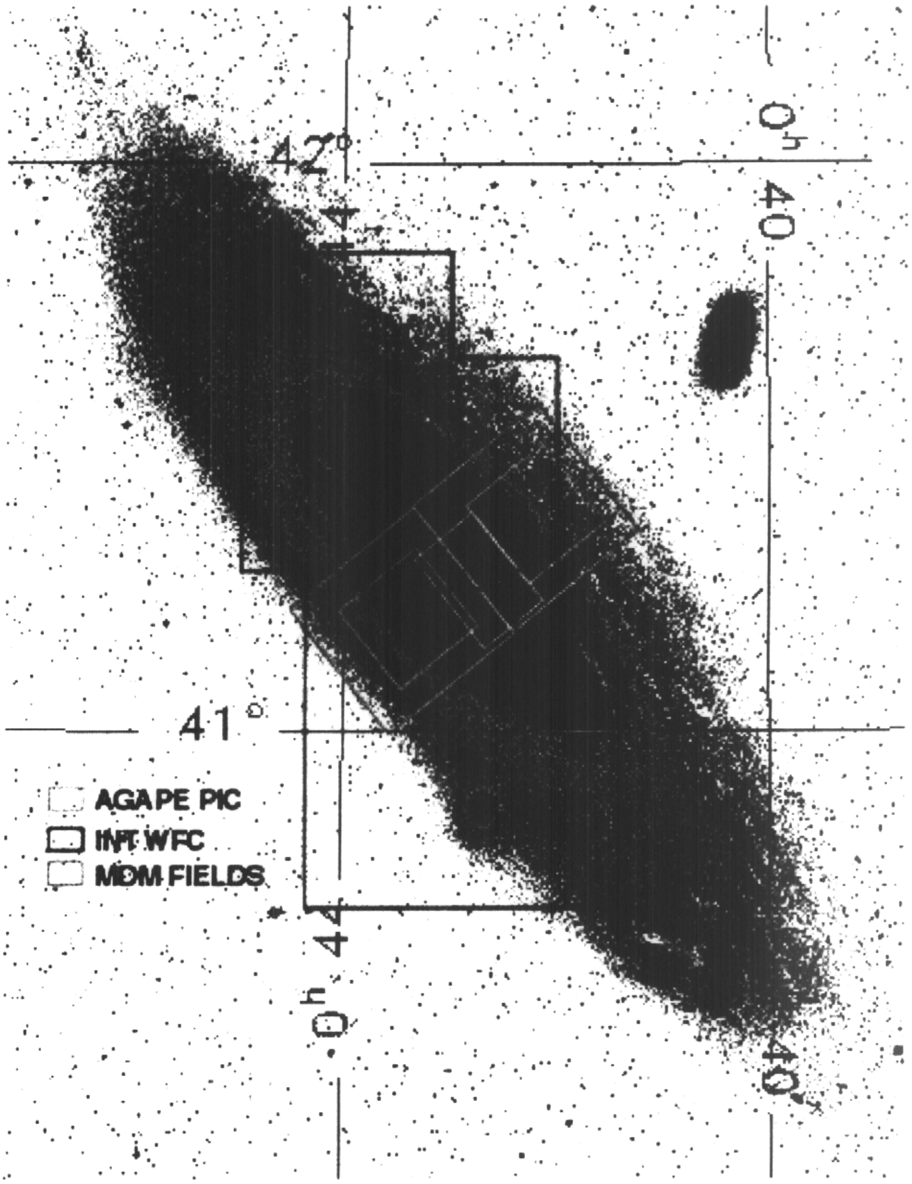
RAS meeting
March 12th 1999

Why Andromeda?

- our nearest giant neighbour
- not dissimilar to our own Galaxy → provides a test of our Galaxy's uniqueness
- well constrained rotation curve and surface brightness profile → reduced model uncertainties
- unambiguous MACHO signature:



asymmetric signature cannot be reproduced by Milky Way MACHOs, stellar self-lensing or by variable stars → definitive test for M31 MACHOs!


42°
41°
0h 40
0h 44
40'
AGAPE PIC
INT WFC
MDM FIELDS

Point - AGAPE M31 (2.5 m INT)

(Pixel lensing)

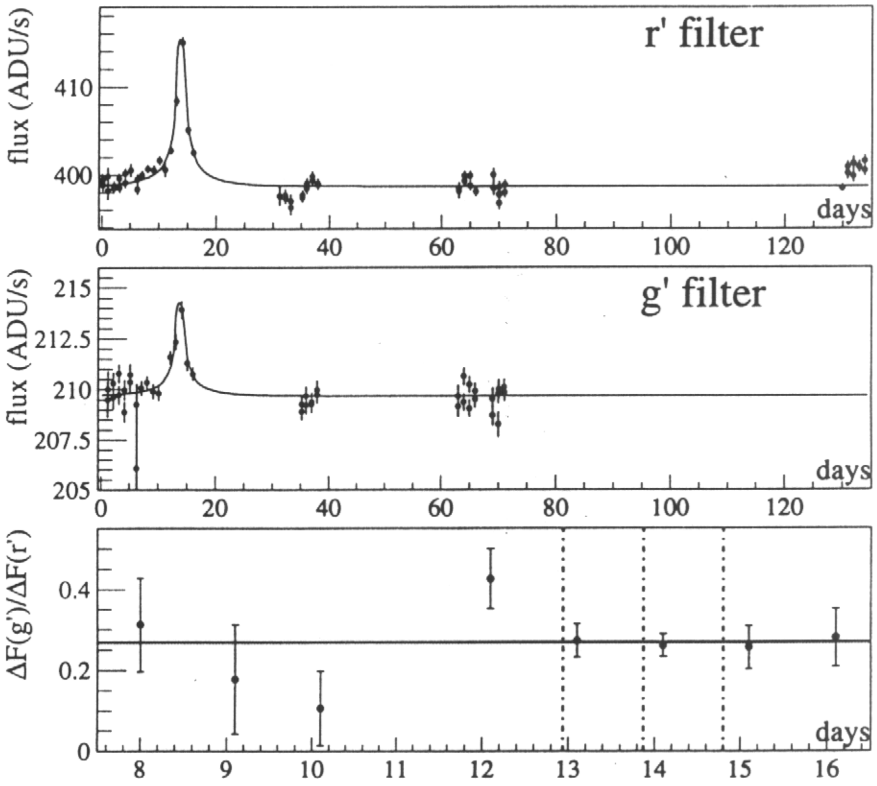


Fig. 1.— Panels (a) and (b) show the flux in r' and g' against time in days. Panel (c) is a zoom centred on the event that shows the variation of the ratio of the flux change in the two passbands $\Delta F_{g'}/\Delta F_{r'}$ with time. The vertical lines are centred on t_0 and are separated by 0.9 days, i.e., half the full width at half-maximum. The days correspond to $J - 2451392.5$ where J is the Julian date.

$T \sim 10$ Tage

➔Dark matter in the halo could, at least partially, be made of *cold molecular H_2– clouds.*

See: –De Paolis, Ingrosso, Jetzer, Roncadelli:

PLR 74 , 14 (1995),

A&A 295 , 567 (1995), 299, 647 (1995),

Int. J. Mod. Phys. D5 , 151 (1996),

MNRAS 294, 283 (1998),

ApJ 500 , 59 (1998), 510 , L103 (1999)

....

Similar ideas have been discussed by:

–Pfenninger, Combes, Martinet A&A 285, 79 (1994)

–Gerhard and Silk ApJ 472, 34 (1996)

–Fabian and Nulsen MNRAS 269, L33 (1994)

–Sciama, MNRAS 312, 33 (2000)

–.......

Dark clusters of MACHOs and H_2– clouds

- ➔"Same" scenario as for the formation of globular clusters.
- ➔The protogalaxy fragments into proto–globular clusters (PGC)

of mass $\sim 10^6\ (R/kpc)^{1/2}\ M_\odot$

and size $\sim 10\ \ (R/kpc)^{1/2}$ pc

(R: galactocentric distance) .
At distances larger than 10–20 kpc H_2 is not dissociated by UV flux –> cooling is more efficient–> subsequent fragmentation –> Jeans mass can be as low as:

$$\sim\ 10^{-1}-10^{-2}\ M_\odot$$

See: –Palla, Salpeter, Stahler ApJ 271, 632 (1983)

➔Thus PGC clouds fragment into smaller clouds, some of which can form MACHOs, whereas others remain there as clouds.

–>formation of dark clusters of MACHOs and H_2- clouds for

$$R \geqslant 10-20\,kpc$$

Observational tests

γ–ray flux produced by halo molecular clouds

- ➔Cosmic rays (protons) from the disk of the galaxy diffuse in the halo.
- ➔Scattering pp–> π^0...–> γγ +... Luminosity of cosmic rays of our galaxy:

$$L_G \sim 10^{41} \text{ erg/s}$$

- ➔Assuming the same energy dependence for cosmic rays as measured on Earth:

$$E^{-2.7}$$

- ➔The power a in E^{-a} depends on the diffusion process undergone by the cosmic rays.
- ➔Indeed near the galactic center in the disk a ~2.45 (M. Mori ApJ 478 , 225 (1997)).

- ➔On the Earth it is $a \sim 2.7$.
- ➔In the halo it could be different.
- ➔Cosmic ray confinement in the galactic halo: it is an open problem!
- ➔To get an estimate we consider an extension of the diffusion model.

  (Berezinsky et al.: "Astrophysics of Cosmic Rays", Amsterdam, North–Holland, 1990)
- ➔The escape time from the halo is then:

$$t_{esc}^{H} \simeq \frac{R_H^2}{3D_H(E)}$$

$R_H \simeq 100\, kpc$: extension of the halo
$D_H(E)$: diffusion coefficient

$D(E) \simeq D_0 \simeq 3\times10^{38}\, cm^2 s^{-1}$ in the non relativistic regime (radio observation in clusters of galaxies).

➔For $E \leq 10^3\,GeV$ -> $t^H_{esc} > t_0 = 10^{10}\,yr$
(~ age of Galaxy)

Since proton flux scales as $E^{-2.7}$, protons with $E \leq 10^3\,GeV$ give the leading contribution to the cosmic ray flux.

➔This way one can estimate the expected γ–ray flux (e.g. $\theta = 90^o$) :

$$\Phi(E > 0.1\,GeV) \simeq f \times 10^{-5}\,\frac{photons}{cm^2\,s\,sr}$$

$$\Phi\,(E > 1\,GeV) \simeq f \times 10^{-6}\,\frac{photons}{cm^2\,s\,sr}$$

f: fraction of halo dark matter in form of cold H_2–clouds (we assume $f \simeq 0.5$)

See:– F. De Paolis, G. Ingrosso, Ph. Jetzer, M. Roncadelli, PRL 74, 14 (1995)

- ➔Possible evidence: observation of γ–ray emission from the halo sorrounding the galaxy:

$$\Phi\left(E>1\,GeV\right)\simeq 10^{-6}\,\frac{photons}{cm^2\,s\,sr}$$

See:– D. Dixon et al. New Astronomy 3, 539 (1998)

- ➔The observed γ–ray distribution can be explained best by models with a flattened halo distribution with flattening q~0.3–0.5.

See: – De Paolis, Ingrosso, Jetzer, Roncadelli ApJ 510, L103 (1999)
– Kalberla et al. A&A 350, L9 (1999)

EGRET Messungen

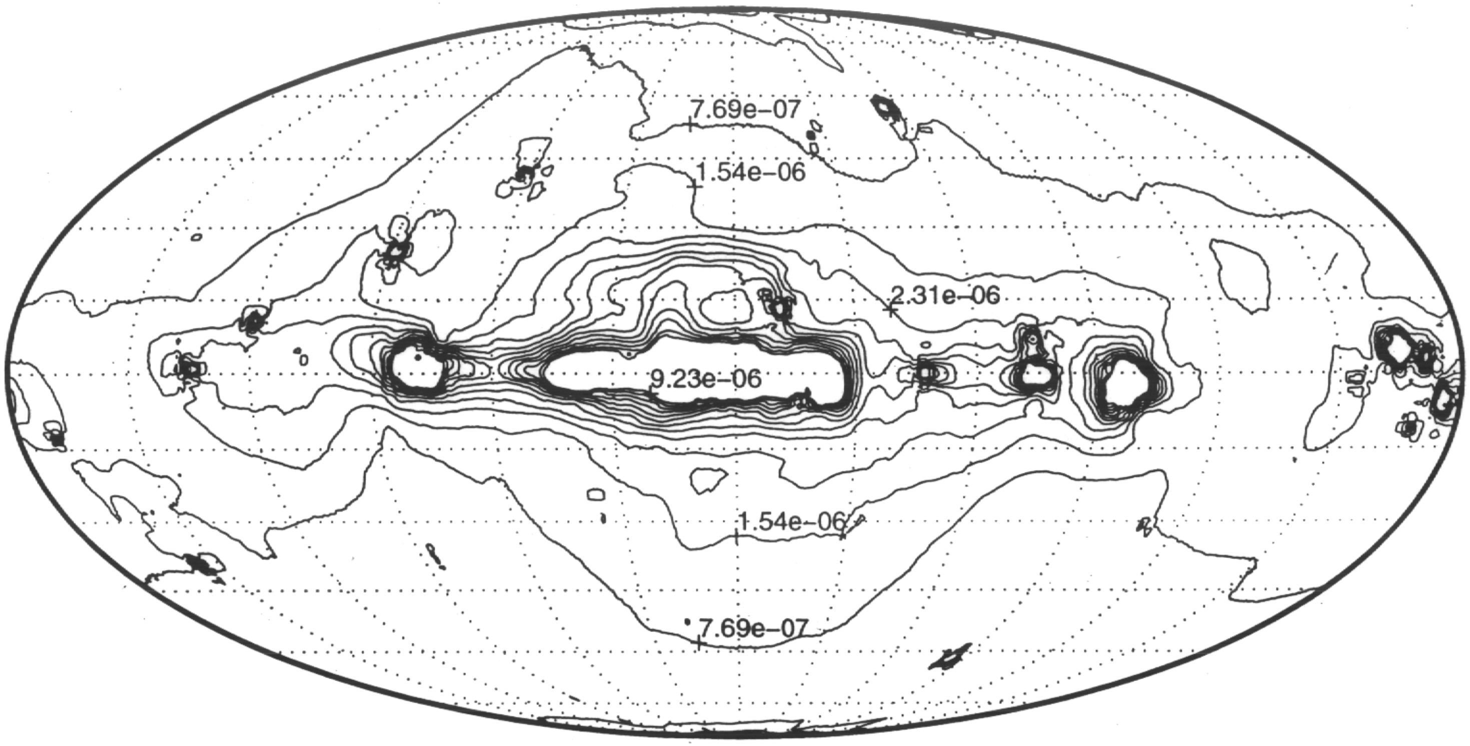
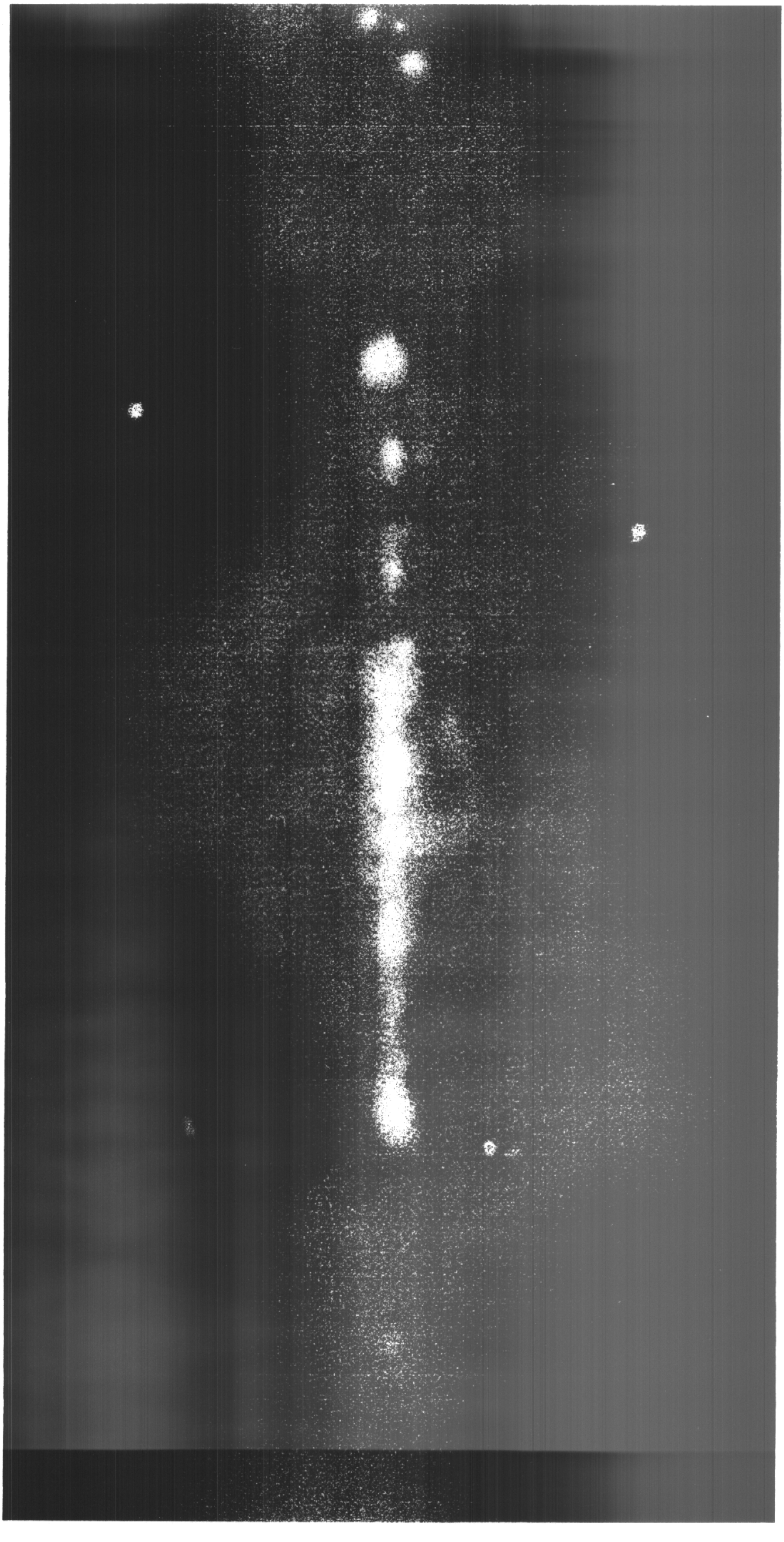
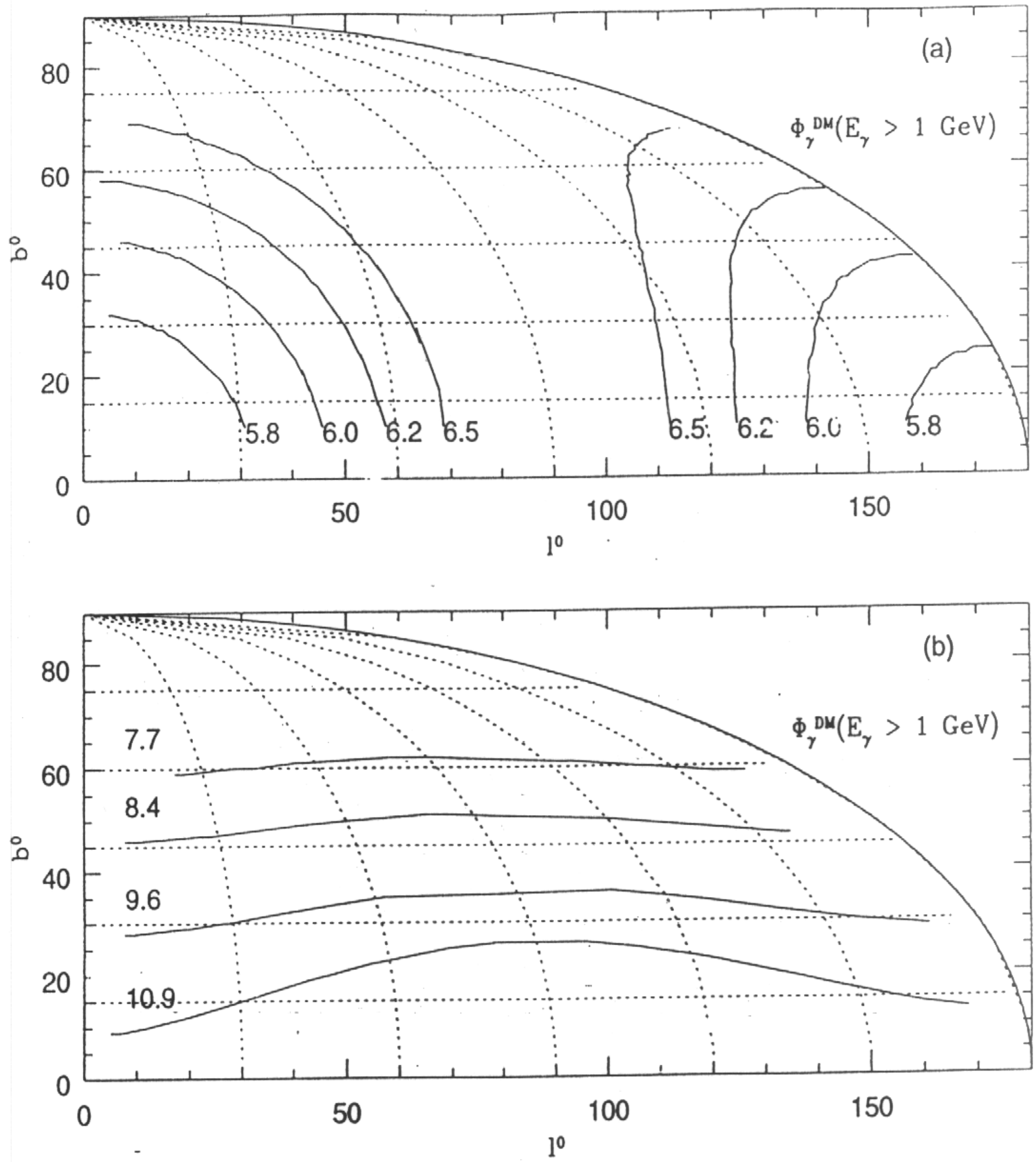


Fig. 3





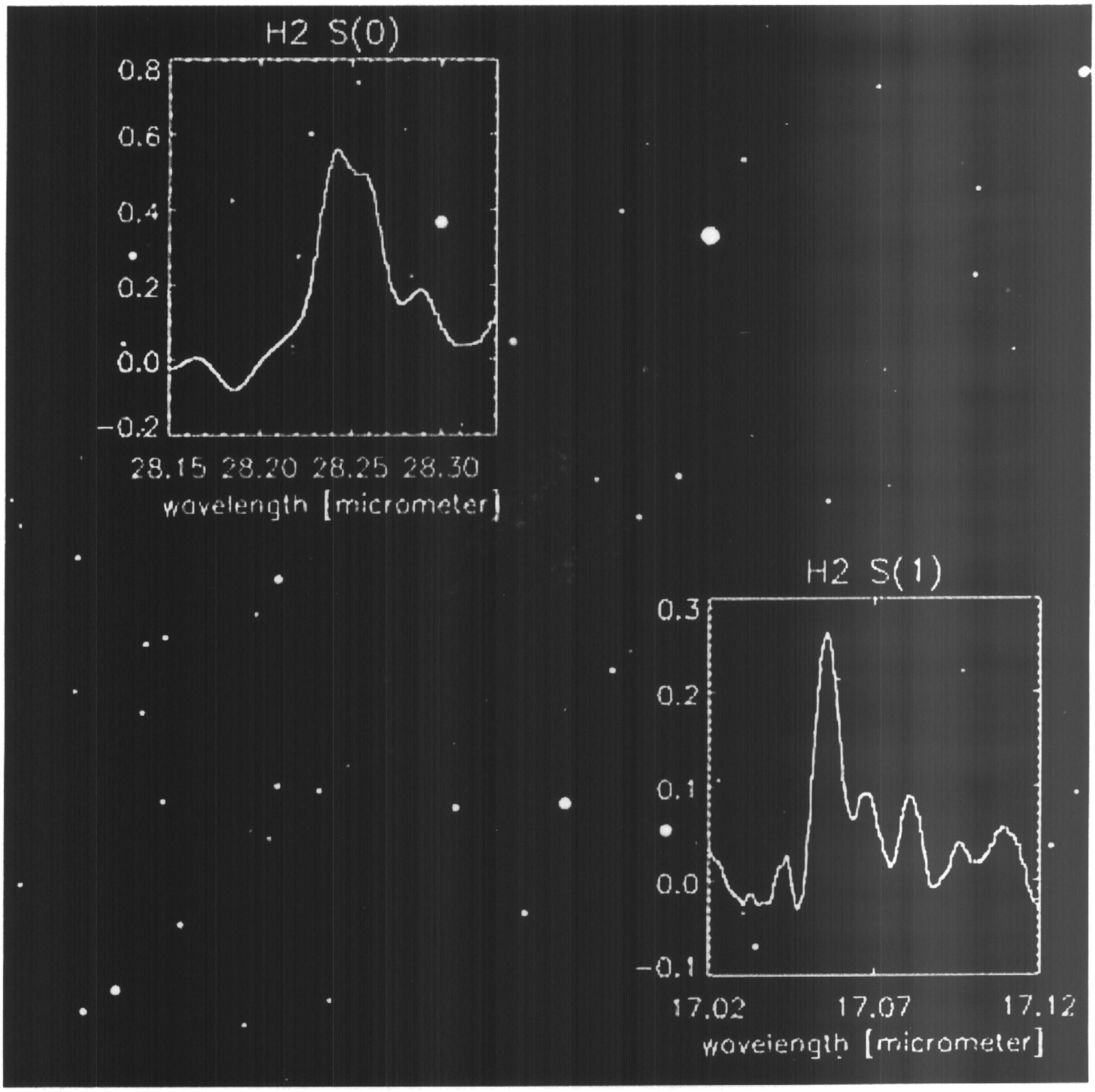
a) Spherical halo

b) Flattened halo q = 0,5

Fig. 2. Contour values for the γ-ray flux due to the DM at $E_\gamma > 1$ GeV are given for the indicated values in units of 10^{-7} γ cm^{-2} s^{-1} sr^{-1}, in the cases: (a) spherical halo, (b) flattened halo with $q = 0.5$.

- F. De Paolis, G. Ingrosso, P. J., M. Roncadelli
  ApJ 510, L103 (1999)

  and NJP 2 (2000) 12


H2 S(0)
0.8
0.6
0.4
0.2
0.0
−0.2
28.15 28.20 28.25 28.30
wavelength [micrometer]
H2 S(1)
0.3
0.2
0.1
0.0
−0.1
17.02
17.07
17.12
wavelength [micrometer]

THE ASTROPHYSICAL JOURNAL, 522:L29–L33, 1999 September 1

FIRST EXTRAGALACTIC DIRECT DETECTION OF LARGE-SCALE MOLECULAR HYDROGEN IN THE DISK OF NGC 891[1]

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ABSTRACT

We present direct observations of molecular hydrogen in the disk of the nearby edge-on spiral galaxy NGC 891. With *Infrared Space Observatory*'s Short-Wavelength Spectrometer (SWS) it has been possible, for the first time, to observe the lowest pure rotational lines of H_2 [$S(0)$ at 28.2 μm and $S(1)$ at 17.0 μm] at eight positions throughout the stellar disk of NGC 891. Both lines have been detected at all the surveyed positions out to 11 kpc north of the center of the galaxy. An H_2 rotation curve is derived, and we compare H_2 radial profiles with CO and H I data. The observed line ratios indicate relatively warm (T = 150–230 K) molecular clouds scattered throughout the disk in addition to a massive cooler (T = 80–90 K) component which dominates the signal in the outer regions. For H_2 ortho/para ratios of 2–3, the cool gas has typical edge-on column densities $(1-3) \times 10^{23}$ cm^{-2} (or $\sim$3000 $M_\odot$ pc^{-2}), in which case it outweighs the H I by a factor of 5–15. This factor matches well the mass required to resolve the problem of the missing matter of spiral galaxies within at least the optical disk. The newly discovered cool H_2 component would be less massive in the case in which its dominant ortho/para ratio is near unity. We address the thermal balance of this component by a comparison with [C II] 158 μm data. When combining the new coolish molecular gas results with recent SCUBA cold dust observations of NGC 891, the total gas-to-dust ratio at $r < 12$ kpc remains around 200.

Subject headings: dark matter — galaxies: individual (NGC 891) — galaxies: ISM — ISM: molecules

1. INTRODUCTION

The gaseous interstellar medium in galaxies consists essentially of atomic and molecular hydrogen. While atomic hydrogen has been extensively mapped in the 21 cm line in many galaxies and found to account for roughly 10% of their dynamic mass, their H_2 content is very uncertain, since it is estimated only indirectly.

Before the launch of the *Infrared Space Observatory* (*ISO*), H_2 emission in external galaxies was only detected in rovibrational lines near 2.1 μm, from typically 10^4 $M_\odot$ of H_2, heated to temperatures of $\sim$2000 K in the centers of starburst, active, and (ultra)luminous infrared galaxies. At lower temperatures, these lines are too faint, and most of our knowledge about the H_2 content comes from observations of CO, assuming a CO/H_2 conversion factor derived for Galactic giant molecular clouds (e.g., Solomon et al. 1987).

ISO's Short-Wavelength Spectrometer (SWS; de Graauw et al. 1996) provides a unique possibility to observe moderately warm H_2 directly in the lowest purely rotational quadrupole transitions $S(0)$: J_u–J_l = 2–0 at 28.2188 μm and $S(1)$: J_u–J_l = 3–1 at 17.0348 μm, belonging to respectively the ortho (J-odd) and para (J-even) series. The ortho/para ratio (hereafter o/p) will be 3 if set by the ratio of statistical weights.

The first extragalactic detection of these lines in the central, relatively warm, and star-forming region of a galaxy was reported for NGC 6946, and we refer readers to Valentijn et al. (1996b) for further details of the survey. For NGC 6946, the observed line ratio [$S(0)/S(1) \sim 0.15$] indicated a temperature of this gas component of 170 K for an o/p = 3. A significant upper limit on the $S(2)$ (12.3 μm) line flux was used to constrain the o/p to $\geq$2, a value which is also commonly found for photon-dominated regions (PDRs).

Complementary to the H_2 rovibrational line surveys and most of the extragalactic *ISO* program, we have selected a relatively normal, nonstarbursting galaxy, NGC 891, and surveyed its disk. We positioned the SWS apertures at eight positions along the galaxy's major axis: out to 11 kpc north and 8 kpc south of the nucleus. We have selected this target because of the expected high column densities from an edge-on disk and because of its proximity (we assume here a distance of 9.5 Mpc).

2. OBSERVATIONS

We observed each line for $\sim$1500 s with the SWS grating (AOT 2 observing mode) using the BIBIB Si:As detector array, which has the advantages of the near absence of hysteresis effects and a very stable (within a few percent) response. The in-flight flux calibration (Schaidt et al. 1996) of this detector matched within 10% to the preflight value measured on a blackbody of known temperature. However, in flight, the effects of impact of cosmic rays on both the detectors and the electronics were severe, and we had to develop dedicated glitch recognition and removal programs (Valentijn & Thi 1999). Thus, we could reduce the effective noise level by a factor of $\sim$4 to $\sim$0.1 Jy and achieve spectra in which the noise fluctuations are nearly normally distributed. One position, at 11 kpc north, was observed in total for 4 hr as a confirmation of our key results.

Figures 1 and 2 show our observational data. We have detected both lines at all the observed positions at a signal-to-

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[1] Based on Observations made with *ISO*, an ESA project with instruments funded by ESA member states (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) and with the participation of ISAS and NASA.

[2] Now at Kapteyn Institute, Groningen, The Netherlands.

Is Dark Matter Just Plain Hydrogen?

SEVERAL KINDS OF UNSEEN "DARK MATTER" are either known or suspected to exist throughout the universe. One kind of invisible matter adds unseen mass to individual galaxies, above and beyond a galaxy's visible stars and interstellar matter. Swarms of brown or white dwarfs, yet-to-be-discovered atomic particles called WIMPs or axions, and hypothetical "quark nuggets" have been proposed to account for it.

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NGC 891, an edge-on spiral galaxy well known to amateur deep-sky observers, contains enough molecular hydrogen to account for all the "missing mass" in a typical spiral. This high-resolution image was taken with the WIYN Telescope on Kitt Peak in Arizona.

But the dark matter in galaxies may not be so exotic or even very dark. According to two Dutch astronomers, most or all of it may be ordinary molecular hydrogen (H_2), which, unlike atomic hydrogen (H), is invisible except at certain infrared wavelengths.

Using the European Space Agency's Infrared Space Observatory (ISO), Edwin A. Valentijn (Kapteyn Institute, Groningen) and Paul P. van der Werf (Leiden Observatory) detected huge amounts of relatively warm molecular hydrogen in NGC 891, an edge-on galaxy 30 million light-years away in Andromeda. In the September 1, 1999, *Astrophysical Journal Letters* they claim that their result "matches well the mass required to resolve the problem of the missing matter of spiral galaxies."

Molecular hydrogen is notoriously difficult to observe. However, the two lowest rotational energy states of this molecule produce weak spectral lines at the far-infrared wavelengths of 28.2188 and 17.0348 microns, a spectral region covered by ISO's Short Wavelength Spectrometer. A few years ago Valentijn reported the first extragalactic detection of these lines in the center of NGC 6946. Now, the study of NGC 891 reveals that molecular hydrogen is all over the place. Valentijn and van der Werf conclude that the galaxy contains 5 to 15 times more molecular than atomic hydrogen (which is easily observed using radio telescopes). They write, "It is well established that if there is about 10 times as much molecular hydrogen as atomic hydrogen in the disks of spiral galaxies, then the missing mass problem [in galaxies] is solved."

Since NGC 891 is a run-of-the-mill spiral, it is reasonable to assume that other galaxies may harbor similar amounts of molecular hydrogen. But this may be hard to confirm. The current observations are right at the sensitivity limit of ISO's spectrometer. Moreover, the gas in NGC 891 is relatively warm (80° to 90° K) with still warmer patches (150° to 230° K), which makes it easier to spot. A thin background of molecular hydrogen would be much harder if not impossible to detect in our own Milky Way because the faint signal would be smeared across the whole sky.

The gas that Valentijn and van der Werf have detected resides in the galaxy's flat disk. What about the dark matter supposedly in galaxy halos?

Surprisingly, the authors claim that none may be necessary. "Our results give a much stronger footing for the 'ordinary matter' simple solution of the dark-matter problem, in the form of massive clouds in the disks of galaxies," they say. According to Valentijn, the "halo culture" that has grown up around the dark-matter problem might never have arisen if the ISO results had been known earlier. Nevertheless, "the problem is complex enough to avoid drawing quick conclusions," he says. For instance, little is known about the warming mechanism for such huge amounts of gas.

Light Speed Is Colorblind

Different wavelengths of light pass through matter at different speeds; that's why the lenses in your telescope's eyepiece show chromatic aberration. But physical theory states that in a vacuum, electromagnetic radiation of all colors — from gamma rays to radio waves — should travel at exactly the same speed. This is difficult to test accurately on Earth, but Yale University astrophysicist Bradley E. Schaefer has compared the speed of different wavelengths across a significant fraction of the visible universe. In *Physical Review Letters* for June 21, 1999, he compares the arrival times of different kinds of radiation from rapid events such as gamma-ray bursts. He concludes that the speed of light in a vacuum is the same to within two parts in 10^{20} for all wavelengths — an extraordinary degree of precision when compared to almost any other measurement in physics.

Further ways to detect H_2

➔Direct observation of the emission due to the lowest rotational H_2 lines in the infrared ->*ISO*
However, possible only if gas is at temperatures of ~ 100 K.
Possible detection with *ISO* in *NGC* 891.
(Valentijn and van der Werf ApJ 522, L29 (1999))

➔Through *Extreme Scattering Events (ESE):* radio waves are refracted by an ionised external layer of the clouds.
Such events have been observed on the radio emission of quasars.
If due to clouds in the halo, the observed event rate implies that a substantial fraction of halo dark matter is in form of clouds.
(Walker and Wardle ApJ 498, L125 (1998))

➔ H_2 absorption in the UV electronic lines (however low surface filling factor of cold gas ~1%)
Feasible with the *ORFEUS* and *FUSE* satellites.
H_2 absorption has been detected in gas of a high–velocity cloud (HVC) in the Galactic halo.
(Richter et al. Nature 402, 386 (1999))

➔ Some authors have argued that HVCs might represent a considerable fraction of the total mass of the Local Group.
(M. López–Corredoira et al. A&A 351, 920 (1999))

➔ There is some indication that there is an excess in the far–infrared emissivity of our galaxy. Sciama argued that it could be naturally accounted for by a population of cold H_2– clouds .
(Sciama MNRAS 312, 33 (2000))

THE MOLECULAR-HYDROGEN CONTENT OF THE UNIVERSE*

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It seems very probable that the total mass of molecular hydrogen in any large volume of cosmic space is at least as great as the total mass of all other forms of matter in the same volume.

In the first place, the reaction $H + H = H_2$ is perhaps the most exothermic within the realm of conventional chemistry, releasing about 104 kilocalories per mole of H_2. From equilibrium calculations, using the mass-action law for the above reaction at any reasonable effective temperature of interstellar or intergalactic space, it follows that H_2 should be much more abundant than monatomic hydrogen.

It may be objected that thermodynamic equilibrium calculations do not apply directly to interstellar and intergalactic gases, which are subjected to various kinds of high-energy electromagnetic and corpuscular radiations. The concentration of some of the constituent molecules and radicals of these gases may thus be depleted because of dissociation being faster than formation. Our second argument for anticipating a high abundance of H_2 therefore relates to the existence of observable amounts of CH, NH, and CN in interstellar space. The heats of formation of these radicals from the relevant atoms are lower than that for H_2, and their formation by radiative transitions in two-body collisions, although perhaps more favored than that of H_2 from H, is still most improbable.[†] The formation of all of the radicals and molecules from the atoms most probably proceeds from multiple collisions and also occurs on the surfaces of larger bodies from dust particles up to those of planetary size. From the fact that CH and CN are observable in interstellar space, in spite of the fact that the abundances of C and N relative to H are negligible, we conclude that H_2 must be very abundant.

In view of the foregoing considerations I have started making arrangements for observations on the abundance of H_2 in cosmic space. I suggest that the emission line at about 85 μ, which corresponds to the transition from orthohydrogen into parahydrogen, offers the best means to make such observations. Scanning of this wavelength region with "spectrographs" using alkali-halide crystal (residual ray reflection from KBr, for instance) and Golay cells is recommended. Since orthohydrogen has a lifetime of only 300 years, strong emission in the 85 μ region should be expected from the transition of orthohydrogen into parahydrogen.

It goes without saying that if the foregoing conclusions are borne out by observations, present-day cosmologies and ideas about stellar evolution will have to be radically modified.

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* Presented at the San Francisco meeting of the Astronomical Society of the Pacific, June 1959.

[†] The probability for $C + H \rightarrow CH$ to proceed by radiative capture was calculated by H. A. Kramers and D. ter Haar, *B.A.N.*, **10**, 137, 1946 (No. 371). I do not know of any similar calculations for $H + H \rightarrow H_2$.

Outlook

- Mikrolensing has been discovered and is very successful!

- First results are already available: possibly up to $\sim$ 20% of the dark matter in the halo is in form of MACHOs

- Cold H_2 clouds may also contribute to the dark halo matter

- Need for more microlensing observations and new γ-ray measurements with next generation of satellites, like GLAST.