Microlensing in Andromeda

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CHAPTER 1

Introduction

It is a well established fact that the universe contains much more matter than we can observe directly from their emission or absorption properties. All massive objects in the universe move with respect to each other under the influence of their mutual gravitational attraction. This enables us to determine the mass of gravitationally bound systems by looking at their dynamics. From the motions of galaxies within galaxy clusters, we know that these clusters contain at least ten times more mass than we can see in the form of galaxies and intergalactic gas. The rotation of spiral galaxies shows that galaxies themselves are also much more massive than can be explained by the stars and gas that we observe. Modern astronomy faces the disturbing fact that we cannot see and do not understand the nature of at least 90 percent of the matter content of the universe. In this thesis we focus on one possible constituent of this unseen, “dark” or “missing” matter, namely dark, massive, compact objects that might be present in the halos of galaxies. Using the gravitational lensing effect we search for these otherwise impossible to observe objects within the halo of the cosmic neighbour of our Milky Way, the Andromeda galaxy.

1.1 The dark matter problem

The first evidence for the existence of “dark” matter was found in the 1930’s by the American astronomer Zwicky (1933), who tried to determine the mass of the nearby Coma cluster of galaxies. Clusters of galaxies are the largest, gravitationally bound systems in the universe, and can contain hundreds of galaxies. If the cluster is assumed to be roughly spherical and in dynamical equilibrium, the relation between the total mass of the system and the velocities of its members is given by the “virial theorem”. From measurements of the velocities of eight galaxies in the Coma cluster, Zwicky found that the virial mass was much higher than could be explained by the sum of the masses of the individual galaxies. His conclusion was that the cluster contained some kind of unseen, “missing” matter. We now know that hot intergalactic gas in clusters contains much more mass than the galaxies, but this is still not sufficient to explain the dynamical masses of clusters. The dark matter content of clusters is about ten times the mass of the gas and galaxies together.
Figure 1.1 – The H\textsubscript{i}-rotation curve of the spiral galaxy NGC 3198 (van Albada et al. 1985). The line going through the data points is the sum of the two components indicated with ‘disk’ and ‘halo’. The “disk” curve is the rotation curve expected from the stars and gas in the disk of the galaxy. Especially in the outer regions this is by far not enough to explain the observed values. The “halo” component is the contribution to the rotational velocities from the dark matter, needed to obtain a good fit to the observed flat rotation curve.

Masses of galaxies can also be derived from their kinematics. In spiral galaxies the matter is rotating around the center, and by equating the centrifugal force to the gravitational force, the total mass within a certain radius can be calculated from the rotational velocity at that radius. By plotting the rotation velocity, which can be measured from the doppler shift of the emission lines of hydrogen, a so-called rotation curve is constructed. Such a rotation curve traces the gravitational potential in great detail.

The optical rotation curves that seemed to indicate the presence of dark matter in the 1970’s (e.g. Rubin et al. 1980) can still be explained with luminous matter. But when good quality rotation curves became available from radio observations in the first half of the 1980’s, it became clear that also (spiral) galaxies contain dark matter. The 21 centimeter line of neutral hydrogen provides rotation curves out to large distances from the centers of galaxies, because the H\textsubscript{i} usually extends out to several optical radii. In many cases the rotation curves remain flat out to the edge of the H\textsubscript{i} disk, where a keplerian decrease would be expected from the distribution of the luminous matter, since that is strongly concentrated to the center of the galaxies. Because of H\textsubscript{i} rotation curves we know that in spiral galaxies the dark matter contributes up to 90 % of the total mass and that it seems to be especially prevalent in the outer parts. Figure 1.1 shows an example of a rotation curve with the contributions to the rotational velocity due to the different mass components indicated.

The cosmological mass budget is usually given in terms of $\Omega$, which characterizes the overall density of the universe. An $\Omega$ of 1 corresponds to the critical density, or a flat universe. The expansion of a flat, matter dominated universe will slowly grind to a halt, but never completely stop. Currently the luminous baryonic matter content of the universe, $\Omega_{\text{lum}}$ is believed to be only 5 % of the critical density. The total mass budget of the universe, $\Omega_{\text{matter}}$,
is much larger, namely about 30%, implying that the amount of dark matter is five times the
amount of luminous matter. From observations of the fluctuations of the cosmic microwave
background we know that $\Omega = 1$, but the remaining 70% of the energy budget of the universe
is in so-called “dark energy”, causing the expansion of the universe to accelerate. In this
thesis we will examine one possible candidate for making up the 25% of the universe’s mass
budget that is locked up in dark matter.

One way of solving the missing matter problem is assuming that gravity does not work
the way we think on these large scales. There are theories that try to explain the discrepancy
between the luminous and dynamical masses of gravitational systems by modifying the laws
of gravity, such as Modified Newtonian Dynamics (Milgrom 1983), or the overall structure
of the universe, such as brane world theories. The other way of solving the missing matter
problem is to identify and detect the matter that has eluded us so far. Several dark matter
candidates have been suggested, coming forth both from astronomy and from particle physics.

Neutrinos were one of the first particle dark matter candidates. These elementary parti-
cles, that are created in thermonuclear reactions in the cores of stars and during supernova
explosions, were believed to have no or very little mass and are extremely difficult to detect.
That neutrinos do have a mass, albeit very small, is now clear from several sources, including
solar neutrino observations (Ahmad et al. 2002) and particle accelerator experiments (e.g.
Ahn et al. 2003). Although neutrinos can be considered dark matter, they do not solve the
problem, since their contribution to $\Omega$ is only on the order of 1%. Theoretical physicists have
suggested several more elementary particles as dark matter candidates. Since there is no ac-
tual proof of their existence yet, they are popularly called “exotic” particles. Currently the
most promising options being considered are Weakly Interacting Massive Particles (WIMPs),
supersymmetric particles, and axions. Particle accelerators should reach the collision ener-
gies needed to detect these exotic particles within a decade.

Besides particle physics, also astronomy has some dark matter candidates to offer. The
most important astrophysical dark matter candidates are the so-called Massive Compact Halo
Objects (MACHOs), that hardly emit any radiation and therefore are not observed. MACHOs
could be stellar remnants, such as very old white dwarfs, neutron stars or black holes. Pri-
mordial black holes, formed shortly after the Big Bang, could also have ended up in galaxy
halos. In the past decade astronomers have been trying to find evidence for this kind of dark
matter in the halo of the Milky Way indirectly, by using gravitational microlensing.

1.2 Gravitational microlensing

Like all particles in physics, photons are influenced by gravity. According to Albert Einstein’s
General Relativity Theory (GRT), a light ray follows a straight line, or null geodesic, through
space-time, but since space-time itself is curved by gravity, a light ray passing close by a
large mass will be deflected (Einstein 1911). In fact, this phenomenon was not introduced by
GRT. In 1804 the German physicist Soldner calculated the deflection of light due to gravity
based on the laws of Newton (Soldner 1804). GRT modifies the Newtonian result by a factor
two in the deflection angle, merely enhancing this “gravitational lensing” effect. In 1919
the predicted effect was verified by Eddington, who measured the position displacement of a
background star close to the sun during a solar eclipse (Eddington 1920).

Gravitational lensing is now an active field in astronomy. It is the only way of mea-
suring the masses of clusters of galaxies without making assumptions about the dynamical
Chapter 1: Introduction

Figure 1.2 – Around the centers of massive galaxy clusters, strong lensing effects may be seen, when background galaxies are multiply imaged or heavily distorted into large arcs. This image shows the inner region of the rich cluster Abell 2218, observed with the Hubble Space Telescope. Several arcs can be seen, most of which are also part of a systems of multiple images of background galaxies. (Source: HST archive)

state of the system. Other applications of gravitational lensing include measuring the Hubble constant, the extent of galaxy halos, and cosmological parameters. The application of gravitational lensing that this thesis research is based on, is detecting compact objects in galaxy halos using gravitational microlensing. Discussing the theory of gravitational lensing is outside the scope of this thesis, but a short introduction to microlensing follows. An extensive review of lensing theory can be found in the book “Gravitational lenses” by Schneider et al. (1992).

Depending on the parameters of the lens system like the lensing mass, and the distances from the observer to the lens and the lensed background source, the gravitational lensing effect can present itself in different ways. Examples of very strong effects are multiply imaged quasars that are located exactly behind a foreground galaxy. In the centers of rich galaxy clusters, strong lensing effects can also be seen, as background galaxies are multiply imaged and distorted into large arcs (see figure 1.2). If lenses are less heavy or further away from the centers of clusters, the lensing effects are much weaker. In this weak lensing regime, the effect can still be observed by looking for small systematic distortions in a large number of background sources. Even lensing by the large scale structure of the universe can be detected this way.

Microlensing is the term for lensing by stars or objects with stellar masses. When an observer, a foreground star, and a background star are perfectly aligned, the background star will be imaged as a circle around the foreground star. The radius of the circle is called the Einstein radius and depends on the lens mass and the geometry of the lens system. If the alignment is not perfect two images will be formed at approximately the Einstein radius, one on either side of the lens, see figure 1.3. The smaller the angular separation between source and lens, the more distorted and the larger the images are. Because surface brightness is conserved in gravitational lensing, the fact that the images become larger means that the flux received from the source increases and the observed source flux is therefore amplified. For a lens with a stellar mass, the Einstein radius is extremely small, of the order of milli- or even microarcseconds, making it impossible for current telescopes to resolve the Einstein ring or
1.3. MACHOs in the Milky Way

Despite the fact that a near perfect alignment of two stars is rare, it is possible to observe microlensing. In the direction of the center of the Milky Way, the stellar densities are high enough to make it feasible to have a good chance of observing the effect if the luminosity of many stars is monitored. Hundreds of events have already been detected by several groups (e.g. Udalski et al. 2000). Paczynski (1986) was the first to suggest that by monitoring stars in the Large and Small Magellanic Clouds (LMC, SMC) microlensing by MACHO’s in the

Figure 1.3 – Schematic view of how the image shapes and positions change as the source crosses the Einstein circle of foreground lens. For each source position, indicated with the open circles, the two images are shown. The closer the source is to the lens, the larger and more distorted the images. Due to the conservation of surface brightness, larger images mean a higher amplification, which the effect that is observed.

Figure 1.4 – Observed magnitude change of the source star during a microlensing event. The unit $t_0$ corresponds to the time it takes the source to move a distance equal to the Einstein ring radius. Light curves are plotted, for six different values of the impact parameter, $p$, expressed in units of the Einstein radius: $p = 0.1, 0.3, 0.5, 0.7, 0.9$ and $1.1$.

the images. Therefore, the only observed effect of microlensing is the amplification of the source. Thus, a microlensing event will be observed as a temporary increase in luminosity of the source star, as it moves across the Einstein disk of the foreground star. Figure 1.4 shows the magnitude change of the source star as a function of time, for several impact parameters.
Figure 1.5 – Permitted fractions of the total dark halo mass that can be present in compact objects of a certain mass, from the MACHO and EROS microlensing surveys. Both surveys were sensitive to microlensing by halo objects in the mass range $10^{-7} - 10 \, M_\odot$. The red line indicates the upper limit from EROS, i.e. the area above the line is excluded. The MACHO survey indicates that a fraction of 20% of the halo mass is present in compact objects with masses of about $0.5 \, M_\odot$, but this assumes that all detected events are caused by halo lenses, which is a controversial matter. Note that a significant fraction of brown dwarfs is excluded by both teams at a high significance level. Figure adapted from Milsztajn (2002).

Milky Way halo could be observed. Since we are looking almost directly out of the disk of the Milky Way, microlensing of stars in these small satellite galaxies, would directly probe the compact object content of the halo.

Two groups, EROS and MACHO, have monitored millions of stars in the SMC and the LMC in search for microlensing events. Both groups have detected around 25 events in total, resulting in an upper limit of the dark halo mass that can be locked up in MACHO’s of 20%. Figure 1.5 shows the results published by both groups. EROS gives an upper limit to the halo mass fraction in compact objects for a range of masses (Lasserre et al. 2000), while MACHO claims that compact objects with masses in the range of 0.1 to 1.0 \, M_\odot account for approximately 20% of the halo mass (Alcock et al. 2000).

The Magellanic Clouds results should be interpreted with care, for two important reasons. First of all it should be realised that by looking at the MC’s we are only probing one line of sight through the halo. Therefore it is possible that we are looking through an unrepresentative part of the halo. Stellar streamers or debris from disrupted satellite galaxies might enhance the microlensing rate. Second, the location of the lenses in the microlensing events is uncertain. It has been claimed that some or possibly all microlensing events are caused by stars in the MC’s themselves, rather than by objects in the halo (Sahu 1998). Thus, the
MACHO and EROS results should be considered upper limits for the MACHO content of the halo of the Milky Way.

Limits on the amount of MACHO’s that can be present in the halo also come from other considerations. Since the dark halo is assumed to be an isothermal distribution, a MACHO population should also be present in the solar neighbourhood. Very faint, nearby halo objects can be distinguished because of their high proper motion with respect to disk stars. Searches for faint, high proper motion objects suggest that only a few percent of the Galactic dark matter consists of MACHOs. Another hard upper limit for the amount of dark matter that can be in MACHOs is set by constraints on the number of baryons in the universe. Current theories on primordial nucleosynthesis, allow at most 50% of the dark matter in galaxies to be of a baryonic nature.

1.4 Microlensing in Andromeda

The nearby Andromeda galaxy (M31), might be the key to obtain a satisfying answer as to the MACHO content of galactic dark matter halos. Studying the Milky Way halo with microlensing is difficult because the MCs only provide us with one line of sight. And even if this could give us conclusive information, it would still be a sample of one halo. More halos need to be studied to enable a general picture of the importance of MACHOs for the dark matter budget.

Crotts (1992) was the first to outline the potential rewards of a microlensing survey of M31. The stars in M31 can act as source stars for microlensing by Galactic MACHOs, thus providing a whole new line of sight through the Galactic halo. More important, though, are the possibilities for studying the dark halo of M31 itself. Because it is an external galaxy, many different lines of sight through its halo can be probed. Due to M31’s high inclination, the microlensing optical depth should vary strongly over the face of the galaxy, as is shown schematically in fig. 1.6. The exact way in which the optical depth changes as a function of position depends on the geometry of the halo. For M31 MACHOs very high microlensing optical depths (lensing probability per star) can be achieved, since lines of sight through the densest regions of the halo are available. Optical depths can reach up to ten times higher than for the Galactic MC surveys and measurement of the optical depth as a function of position can constrain halo models.

Unfortunately, because M31 is at a distance of almost 800 kpc, most of the stars are unresolved by ground based telescopes. Conventional methods for monitoring the brightness of stars as used by the surveys towards the MCs can not be used in the overcrowded M31 fields. Microlensing events can be detected for which the source star is only resolved while it is being magnified. Microlensing of unresolved stars is generally called “pixel lensing” and was theoretically formalized by Gould (1996).

The method suggested by Crotts (1992) to solve this problem consists of registering a time sequence of CCD images to a common coordinate system, scaling them to the same photometric intensity and subtracting them from a high signal-to-noise reference image. Stars that vary in brightness will show up as positive or negative point sources in the difference frame, depending on whether they brightened or faded with respect to the reference frame. Tomaney & Crotts (1996) were the first to show that this technique worked in M31. To cope with seeing differences between the reference frame and the individual frames from the sequence, Tomaney & Crotts (1996) use a PSF (point spread function) matching scheme,
Figure 1.6 – Schematic representation of M31. Due to the inclination of 78° of the galaxy, the path length through a possible MACHO halo is much longer towards the far side of the disk than towards the near side. Therefore, the microlensing event rate should show a strong asymmetry, if compact objects are a significant contribution to the dark matter.

where prior to subtraction the better seeing image is degraded to the same seeing as the worse seeing image.

The first large microlensing survey in M31 was performed by Uglesich et al. (2004), who surveyed two fields covering 560 arcmin$^2$ from 1997 to 1999. Due to the rather small fields and sparse time sampling this resulted in 3 microlensing events. This sample is too small to draw strong conclusions about the MACHO content of the M31 halo. Currently, several groups are performing microlensing surveys towards M31, including MEGA (de Jong et al. 2004), POINT-AGAPE (Paulin-Henriksson et al. 2003), WeCAPP (Riffeser et al. 2003) and several candidate microlensing events have already been reported. The work presented in this thesis is part of the MEGA (Microlensing Exploration of the Galaxy and Andromeda) survey. MEGA uses several telescopes, including the 2.6m Isaac Newton Telescope (INT) on La Palma, the 4m Mayall telescope at Kitt Peak and the 1.3m and 2.4m telescopes at the MDM-Observatory on Kitt Peak. Because of the larger survey area of ~0.5 deg$^2$ and much better time sampling MEGA should be able to detect many more microlensing events. The POINT-AGAPE group uses the same INT data as MEGA, as well as part of the 1.3m MDM data set, but uses different techniques to detect and photometer variable sources in M31. Finally, WeCAPP are observing the central region of M31 in a ~300 arcmin$^2$ field with 1m class telescopes with very dense time sampling. Several candidate microlensing events have already been reported by these surveys.

1.5 Brief thesis outline

In order to obtain a definitive answer on the question of the importance of MACHOs in the halo of M31, the MEGA project was designed. For this project, two fields in M31 were monitored for microlensing during four years, using several telescopes with wide field imaging capability. The research described in this thesis involves the reduction and analysis of the MEGA data obtained with the Wide Field Camera (WFC) mounted on the Isaac Newton Telescope (INT) on La Palma.

In chapter 2 the data set and the reduction and analysis techniques are described. Chapter 3 is the first paper that was published based on the research in this thesis. It describes the candidate microlensing events that were selected after analysing about half of the total...
amount of data and a careful attempt at interpreting these, regarding a possible microlensing halo around M31. Apart from detecting microlensing events, this microlensing survey also results in a very large set of variable star lightcurves. These variable stars turn out not to be just a by-product, they provide important information about the source population for microlensing necessary for a correct interpretation of the microlensing results. In chapter 4 the classification of detected variables in different classes is described. Cepheids and Long-period Variables are used to study the distribution of the microlensing source populations in M31. Chapter 5 contains the final microlensing results of the full 4-year survey with the Isaac Newton Telescope. In chapter 6 we study the possibility of performing a microlensing survey in the elliptical galaxy Centaurus A with the future VLT Survey Telescope. Finally, chapter 7 contains a summary of the work presented in this thesis, a short discussion of the future work and the prospects of microlensing, and the final conclusions of this thesis.