Microlensing in Andromeda

de Jong, Jelte Teun Anne

CHAPTER 7

Summary, outlook and conclusions

IN this thesis an attempt was made to answer an important astrophysical question: is a significant part of the dark matter in the Andromeda galaxy (M31) locked up in compact objects? It is a cliché that scientific research usually raises more new questions than answers old ones, but also in this case the research that was carried out has spawned many new problems and issues. At the end of this booklet it is therefore good to summarize the results and new questions, and say a few words about the extension of the current work and about the future prospects of the field of extragalactic microlensing.

Thesis summary

The motivation for the microlensing survey described in this thesis has been the possible detection of baryonic dark matter in the form of a large population of dark compact objects in the halo's of galaxies. As outlined in chapter 1, the microlensing surveys towards the Magellanic Clouds have shown that not all Galactic dark matter is locked up in compact objects, but a non-negligible fraction of up to 20% might be (Alcock et al. 2000; Lasserre et al. 2000). A microlensing search in M31 has several advantages over the Magellanic Cloud surveys (see section 1.4). Perhaps the most important one is that microlensing by dark halo objects (MACHOs) should be easily distinguishable from microlensing by stellar lenses, because of the high inclination of the disk of M31 with respect to our line-of-sight, inducing a strong asymmetry in the halo-lensing event rate, but not in the self-lensing rate (figure 1.6). One vital assumption for this to work is that the underlying microlensing source population is symmetrically distributed within M31.

M31 is much further away than the Magellanic Clouds, about 780 kiloparsec, and this makes it impossible to perform photometry on any but the brightest individual stars. For the work presented in this thesis a special technique, pioneered by Tomaney & Crotts (1996), has been used: Difference Image Photometry. The basic principle behind the method is easy to understand. When two CCD images of the same stellar field are subtracted from each other, the stars that have changed in brightness in the time between taking the images will show up as bright or dark spots in the otherwise empty "difference image". Of course great care has to be taken with this technique, and all the details of the procedure used for the work presented in this thesis are discussed in chapter 2.

Apart from these technical issues related to the detection and photometry of variable sources in the overcrowded fields in M31, the confusion with variable stars is a more astrophysical problem concerning the detection of microlensing events. Colour criteria can be used to separate out certain classes of variable stars. Furthermore, standard microlensing events should be achromatic, whereas variable stars often show strong colour evolution during their pulsation period. The most reliable method to distinguish a candidate event from a variable star is to monitor the baseline for a long time and check for periodic variability. In chapter 3 we present an analysis of the first two observing seasons at the Isaac Newton Telescope (INT). Because of this relatively short baseline we use a colour criterium as part of our microlensing selection scheme (figure 3.3). Of the 14 candidate microlensing events found in chapter 3, 4 turn out to be variable stars during the analysis of the complete 4-year data set in chapter 5, when subsequent variability was seen.

The importance of chapter 3 mostly lies in the fact that it showed the ability of our method to detect candidate microlensing events in M31. Although the analysis of the sample of 14 candidate events is very crude, it seems to indicate that halo-lensing is indeed significant. Since the detection efficiency for microlensing has not been determined and a comparison with microlensing models is therefore not possible, the spatial distribution of the sample is compared to the spatial distribution of the variable stars with periods between 150 and 600 days. The motivation for this is that the variable stars can be used as a rough indication of the detection efficiency across the fields. The result of this comparison is that the candidate events are distributed more asymmetrically than the variables, with a surplus of events on the far side. Although the significance of this result is low, it is still an indication of the presence of a microlensing halo.

Since a microlensing survey is in fact a variability survey, it has many more applications than just the detection of microlensing events. Probably the most important by-product of our INT survey is the catalogue of tens of thousands of variable stars that are detected and photometered. In chapter 4 we show that the lightcurves produced in this survey can be used to identify a variety of classes of variable stars, including Cepheids, long-period variables, eruptive variables, RV Tauri stars and eclipsing binaries. But apart from forming a separate research opportunity, the variable stars turn out to serve an important purpose for the microlensing results as well. The discovery by An et al. (2004a) that the distribution of detected variable stars in M31 shows a near-far asymmetry, makes it clear that there are other effects than halo-lensing that can cause an asymmetry in the microlensing event rate. However, An et al. (2004a) suggest that the main reason for the variable star asymmetry is differential extinction within M31, and in section 4.4 we argue that extinction in fact might be the only reason. This means that when these extinction effects are taken into account properly, the spatial distribution of microlensing events can still be used to constrain the significance of halo-lensing.

Chapter 5 is the microlensing analysis of the complete four-year INT data set and therefore the chapter in which we address the main scientific issue of this thesis. With the four-year INT data set supplemented with data from the Mayall 4m. telescope at Kitt Peak, we have very long baselines, so that even variables with periods up to a few years will show more than one episode of either increased or decreased brightness. Because of this we do not have to use an explicit colour criterion to select microlensing events, but can rely on flat baselines and good standard microlensing fits to well-sampled peaks in flux. The fully automated selection procedure described in section 5.4 results in 14 candidate microlensing events, 10 of which were also in our sample in chapter 3 and 4 were not. Through Monte Carlo simulations we determine the detection efficiency for standard microlensing events, enabling us to compare the sample of events with model predictions. For the model predictions we use self-consistent models (Widrow & Dubinski 2005) for M31, and combine these with the detection efficiencies and an extinction model derived in section 5.7. The number of events due to self-lensing within M31 that the models predict ranges between 11 and 15, while for a 100% MACHO halo 30 to 40 events are expected. Based on the total number of events, we find that the most probable MACHO halo fraction f varies between 0 and 0.1 depending on the model. Our event rate analysis is consistent with a total absence of MACHOs as the confidence intervals for all of our models include $f = 0$. We cannot exclude some MACHO component, but a MACHO fraction of $f > 0.3$ is excluded at 95% confidence for almost all models. Due to extinction self-lensing causes an asymmetric microlensing distribution, although the asymmetry due to halo-lensing is a factor 2 or more higher. The asymmetry in the data is very high and cannot be explained even by pure halo-lensing. This high asymmetry is largely caused by three events for which there are reasons to believe they are not due to any of the modeled populations. One event is likely to be caused by a lens in M32 (Paulin-Henriksson et al. 2002). The other two are located very far out in the disk and are very difficult to explain with either self-lensing or halo-lensing. Possible explanations include misidentification of variable stars and an extra lens population in the giant stellar stream (Ibata et al. 2001) in front of M31. When ignoring these three events, the data are consistent pure self-lensing models with high extinction. Our conclusion is that both from the observed number of events, and from their spatial distribution we find no evidence for the presence of MACHOs in the halo of M31.

When something difficult has been achieved, there is often the tendency to try and take things even further. Now that several groups have detecting microlensing in M31, it is therefore a logical step to extend this kind of work to even more distant targets. In chapter 6 we consider the prospects of a microlensing survey toward the giant elliptical galaxy Centaurus A (NGC 5128) with OmegaCam, the wide-field camera that will be mounted on the VLT Survey Telescope (VST). Centaurus A is the target of choice because it is the nearest large elliptical galaxy, thus providing the best opportunity of studying an early type galaxy. We use INT data of M31 to simulate a deep survey in Centaurus A with the VST and analyse this simulated data set with the same methods as used for our M31 survey. At the distance of Centaurus A, $\sim$4 Mpc, our method still works fine for the detection and photometry of variable sources. However, even for a deep survey with exposure times of several hours per night with VST, which has a 2-meter diameter primary mirror, the rate of detectable microlensing events is estimated to be in the order of 5 to 10 per year. This is obviously not a satisfactory efficiency for such a project and we therefore suggest that space observatories are probably the only way to improve the signal-to-noise sufficiently to make a project like this worthwile.

Outlook

The immediate continuation of the work presented in this thesis will consist of combining the data sets obtained at the different telescopes used by the Microlensing Exploration of the Galaxy and Andromeda (MEGA). Apart from the INT these are the Mayall 4m telescope at the Kitt Peak National Observatory (KP4m), the 1.3m McGraw-Hill and the 2.4m Hiltner telescope at MDM Observatory, and the Subaru and Hubble Space Telescope. This will further improve the time-sampling of the survey, potentially resulting in new candidate microlensing events, and the latter two telescopes will provide absolute photometry for variable stars and possibly identification of microlensing event source stars. The combined data set will hopefully enable us to draw stronger and more detailed conclusions about the lens and source populations in M31.

Studying the variable stars in M31 is another future goal of MEGA. Especially the combination of INT and KP4m data will be important in this respect, since the INT data offers the best time-sampling and the KP4m the highest sensitivity. The number of detected variable stars will increase by several factors compared to the number of variables presented in chapter 4. The final MEGA variable star catalogue will therefore offer a unique opportunity to study a very large sample of variable stars in a galaxy other than the Milky Way, with the additional advantage that their distribution over the whole galaxy is at hand. And again, also for the study of the distribution of the underlying stellar populations and the differential extinction the variable stars will form an important source of information.

The next challenge in extragalactic microlensing will be extending microlensing surveys to galaxies outside the local group. That detecting microlensing events in such distant galaxies is in principle possible is shown by Baltz et al. (2004), who detect some variable sources in M87, and by our simulations for Centaurus A in chapter 6. However, we note that a problem that might prove even more substantial, concerns the interpretation of the results of a microlensing survey in far-away targets. The further away the target is, the less information one will be able to obtain for individual microlensing events. Thus, the interpretation will rely more and more on the statistical comparison of the sample of detected events with model predictions. An even greater challenge than detecting microlensing events in itself might be modeling the targets in sufficient detail.

In a broader picture, the field of microlensing seems to have shown that both in the Milky Way and in M31, MACHOs do not account for a large part of the dark matter. But microlensing has many other useful applications. Now that an increasing number of events is detected within the Galaxy and better photometry with denser time-sampling is obtained, more detailed information about individual events can be derived. Once space-based optical interferometry missions are operational, their angular resolution will be high enough to measure the centroid shifts in Galactic and even Magellanic Cloud microlensing events. This is called astrometric microlensing, and enables direct determination of the Einstein radius and the relative motion between lens and source. With these extra constraints the lens mass can be determined and also in the case of binary lenses several degeneracies are lifted (e.g. Paczynski 1998; Boden et al. 1998; Han et al. 1999). The study of galactic structure and the stellar mass function will be the most important science driver for the future work in microlensing.

Conclusions

The central question formulated at the beginning of this chapter was: "is a significant part of the dark matter in the Andromeda galaxy locked up in compact objects?" The most honest answer that can be given on the basis of the research presented in this thesis is: probably not.

The complicating factors for constraining the amount of MACHOs in the M31 halo are: 1) extinction also inducing an asymmetric signal in the microlensing event rate and the difficulty of modeling the extinction in detail and 2) the relatively small sample of events, so that detailed conclusions cannot be drawn based on an analysis of statistical nature.

However, it is clear that MACHOs do not account for a large fraction of the mass in the M31 halo. The predicted number of microlensing events due to self-lensing within M31 is quite stable around 11 to 15 in our models, which is consistent with the 14 detected candidate events; the expected number of events due to a 100% MACHO halo is considerably higher, 30 to 40. Based on the number of events we can exclude at 95% confidence that more than 30% of the M31 halo mass is in MACHOs with masses between 0.1 and 1.0 $M_{\odot}$. This is consistent with the limit given by the microlensing results towards the Magellanic Clouds. Two of the candidate events in the final sample are difficult to explain with any known lens population due to their locations far away from the major axis. Another event is probably caused by a lens in M32, rather than M31. There are therefore good reasons to leave these three events out of the analysis. If this is done, self-lensing can easily explain the complete candidate event sample, including the asymmetry in their spatial distribution. Of course, if the MACHOs have much higher masses than the range we probe, the number of halo-lensing events will go down dramatically, so that MACHOs of several tens of solar masses cannot be excluded. However, we must conclude that our results are consistent with pure self-lensing and thus, that we find no evidence for the presence of MACHOs in the M31 halo.