THE LIVING GALAXIES

A survey project with ODI at WIYN

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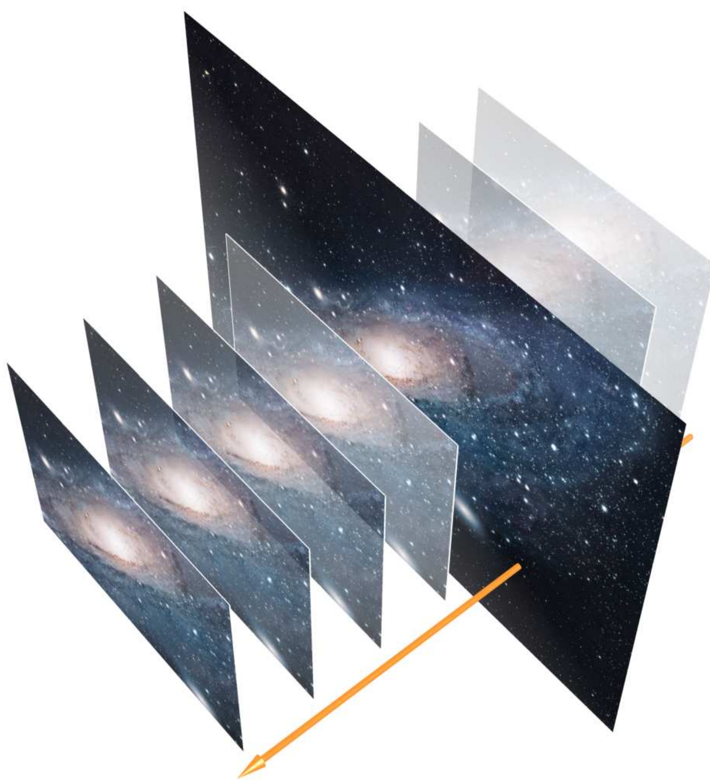


1 Abstract

We propose temporal monitoring of the North-East quadrant of Andromeda (M31), and all the Triangulum galaxy (M33), using the WIYN One Degree Imager (ODI). These surveys will comprise the first systematic studies of optical variability in the two galaxies that sample timescales extending from minutes all the way through to years, and that incorporate multiple filters including Hα. Within the overarching theme of monitoring the 'circadian rhythms' of our closest spiral-galaxy neighbors, our science drivers are (i) to obtain a comprehensive picture of compact-object binaries in outburst, determining rates of different classes of novae and black hole transients; (2) to derive statistics and basic parameters of quiescent symbiotics and high mass X-ray binaries; (3) to establish whole-galaxy censuses of variable massive stars (β Cepheid pulsators and disk-forming Be stars), allowing critical tests of stellar structure and evolution. In addition to these three drivers, we will acquire a superb database for the study of long-period variables, and moreover obtain the deepest Hα exposures ever obtained for M31 and M33.

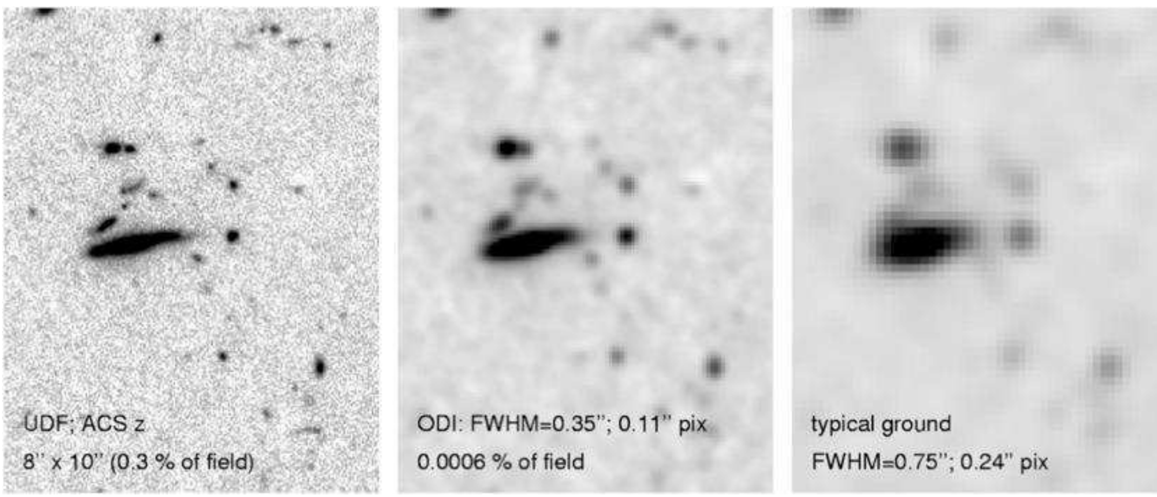


Figure 1: Comparison between an HST ACS image, and the same image degraded to ODI best quality (middle) and best quality of the Mayall 4m telescope at Kitt Peak.

2 Motivation

Throughout history, variable stars have led humans to pay attention to "divine signs" in the sky, and fostered people's curiosity about the Universe. As we enter the second decade of the 21^st Century, the study of these variations as a *survey* endeavor is now moving to center stage. Out of 17 Letters of Intent that the IAU recently received for symposia in 2011, two and large part of a third one are completely dedicated to timing analysis of astronomical sources. With the outstanding image quality of WIYN, coupled with the wide field of ODI, we propose to position UW-Madison at the very center of this drive into the time domain, by undertaking the most comprehensive temporal surveys ever of the closest spiral galaxies to our own galaxy — M31 and M33.

The name of the project — *The Living Galaxies* — vividly encapsulates what we hope to obtain from these surveys. Over the multi-year duration of the project, we will be able to see the galaxies as they've never been seen before — not as frozen entities which are to be studied at a single point in time, but as living ecosystems which show energetic activity and variability across a multitude of timescales. Of course, behind this rhetoric there are solid scientific reasons for long-term, intensive monitoring of M31 and M31, which tie in closely with stellar astrophysics research already undertaken at UW-Madison — specifically, close binaries undergoing mass transfer, and unstable massive stars.

Efforts to understand the fundamental physics governing these system, and to explore the sensitivity to parameters such as metallicity, lie at the forefront of modern astrophysics.

The classes of objects and phenomena we will study are described in Section 3. The observation plan is discussed in detail in Section 4, which includes a table indicating the cadence and filters that are necessary for each of our scientific goals. In Section5 we briefly review previous temporal studies of M31 and M33, and in Section 6 we make the case for ODI being the ideal instrument for the project, explaining why it is competitive in the realm of wide field imagers. Section 7 contains some plans on data analysis and management, and in Section 8 we discuss plans for spectroscopic follow-up to the project. Finally, we present the project team at individual and institutional levels in Section 9, and establish a provisional timeline in Section 10.

3 Science Targets

Our knowledge of the Local Group stellar populations has been greatly expanded in recent years, thanks to high-resolution, wide-field cameras on both ground-based telescopes and on the Hubble Space Telescope (HST). The metallicity dependence of distance indicators such as RR Lyrae and classical-Cepheid pulsators has been studied in several galaxies, and Hertzsprung-Russell (HR) diagrams of extensive regions of Local Group galaxies are revealing their intricate star formation histories. ODI on WIYN, a one-degree-field detector with scheduling flexibility and a substantial number of nights per year allocated to the UW, will furnish an unprecedented opportunity to further improve the study of interacting binary systems, a key element in understanding the distant Universe. Figure 1 shows the typical spatial resolution of ODI, compared with other ground telescopes and with the HST. Although we cannot compete with HST, ODI clearly stands above its ground-based peers, and is an excellent choice for the study of resolved stellar population in nearby galaxies.

Methods and software packages have been devised in recent years to study variability for crowded and even non-resolved stellar population. These will stand us in good stead when monitoring the central 5 arcminutes of M31 and central 3 arcminutes of M33, where crowding and diffuse light make other methods impossible. However, even at larger distances from the core, these rapid methods of image comparison allow the discovery and characterization of variable objects more quickly and efficiently than traditional photometry.

One of the most accurate determinations of the distance modulus of M31 is 24.47$\pm$0.06 (Stanek & Granavich 1998). This distance modulus, comparable to that of M33, implies that we will observe a very large number of optical transients in outburst, and moreover numerous variable massive stars. In the course of this five-year project we will obtain precise statistics on novae and symbiotic systems, explore the behaviour of optical counterparts of eruptive of X-ray binaries (XRB), especially those containing black holes, and learn about the feedback of star formation on interacting binaries.

The white dwarf binaries data will have a significant impact in the search for the progenitors of type Ia supernovae (SNe Ia). We will assess the existence and frequency of other types of binary systems harboring compact objects, and obtain an optical variability database for a large number of other types of astrophysical object. Our project will overlap in time with *Swift*, *XMM-Newton* and *Chandra* monitoring of M31 and M33 in the UV and X-ray, wavelength regions in which close binaries are very luminous. The UV/X-ray exposures will be available to us or to the community in general, allowing us to derive several physically meaningful parameters of these transient objects. In addition, the recently approved Multi-Cycle Treasury HST project on the North-East quadrant of M31, the same region chosen by us, will yield superb reference images at one epoch in several filters, including the UV.

Among periodically variable early-type (OBA) stars, the β Cepheid pulsators are the most luminous, but because of the high cadences needed, they have not been studied well in external galaxies. The instability strips in the upper HRD inhabited by these objects are sensitive to stellar envelope opacities; thus, surveys of large populations of β Cepheids, at a variety of abundances, can be used for stringent testing of laboratory measurements of opacity and other microphysics.

Other early-type targets include Be stars, which episodically eject equatorial material into a Keplerian decretion disk; and luminous blue variables (LBVs), which show eruptive outbursts. The reasons behind both of these irregular phenomena are still poorly understood, and surveys of large populations of each are required to shine light on possible avenues of future research.

3.1 Accreting Systems

Close binaries undergoing mass transfer, especially white dwarf binaries, are the area of expertise of PI Orio, who has been specially involved with the search for candidate type Ia supernovae progenitors in M31, mainly using X-ray observations (Orio 2006, Nelson et al. 2009, Orio et al. 2010). She is currently also involved in spectroscopic classification of the M31 novae, in collaboration with the Asiago and TNG telescopes of INAF (Di Mille et al. 2009; see the numerous IAU Circulars and Astronomer's Telegrams by Di Mille et al. in the reference list). In conjunction with this program, and with her X-ray monitoring of novae and supersoft X-ray sources in M31, Orio has carried out observations of selected areas of M31 with WIYN and the current mini-MO imager (Orio 2006, Orio et al. 2010), yielding deeper and better photometric images (see Fig. 2) than the Local Group Survey of Massey et al. (2006, 2007).

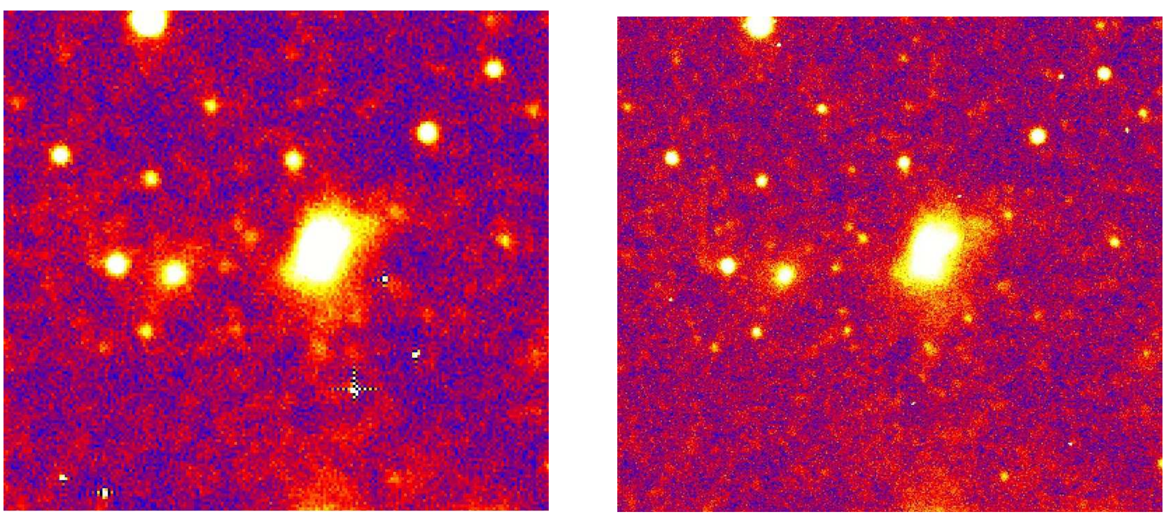


Figure 2: A detail from one of the mini-MO Hα images, in a 0.8x0.95 arcminute area, is shown on the right while on the left we show the comparison with a public LGS image of the same region. The LGS image was obtained in a 5 minutes exposure at the 4m Kitt Peak telescope.

Accreting systems can be studied in two states: in outburst and in quiescence. In outburst we will primarily obtain the light curves of novae and black-hole transients.

3.1.1 Classical and Recurrent Novae (RN) in Outburst

Extragalactic novae are the main tracers of interacting binary stars in general, and also of the *single degenerate* progenitors of type Ia supernovae (SNe). Novae are also excellent indicators of the star formation rate history of a galaxy: the outburst recurs more often in systems containing high mass white dwarfs (WDs), so novae are expected to be more often observed if there has been recent star formation (Yungelson et al. 1997, Neill & Shara 2004, 2005).

Recently, several efforts have been made to measure the nova rate of M31, but they are based on small telescopes and small fields of view (e.g. Darnley et al. 2006, Fliri et al. 2006, Heinze et al. 2008). When normalized to the galaxy's luminosity, the most current estimate, 65 year^{-1} (Darnley et al. 2006), appears to be much higher than the equivalent measure for M33. This difference has been interpreted as an indication that novae are mainly an old population, and seems to be confirmed by

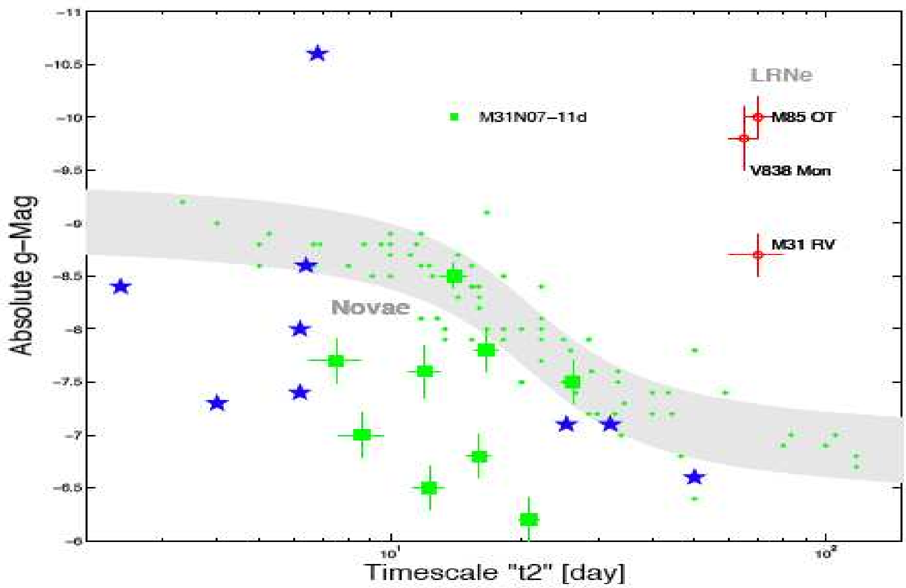


Figure 3: The green squares are putative novae observed in external nearby galaxies by the FastTING team (courtesy of Shri Kulkarni and Mansi Kasliwal). The small green dots in the magnitude versus time for a 2 mag decay are the classical Galactic novae used to calibrate the Maximum magnitude Rate of Decay Relationship (MMRD). Recurrent Galactic novae, occurring on massive white dwarf, and SNe Ia candidate progenitors, are represented with the blue stars and they are not known to obey this relationship. Also shown is M31N07-11d, a RN of M31, and the location of the luminous red variables. It seems that the FastTING is observing mostly RN - this may be because of the frequent sampling that does allows not to miss RN. For this reason we plan observe M31 and M33 at least as once a week.

our study of M31. However, the differences in nova rates are the subject of ongoing debate (e.g. Della Valle et al. 1992, Matteucci et al. 2003) and the M31/M33 comparison is still based on small number statistics for M33 (e.g. Williams & Shafter, 2004) and small regions of the full angular extent of M31.

Rather than continuing with the current practice of extrapolating the nova rate of small fields to other regions of a galaxy (in spite of differences in metallicity and star formation history), we will measure precise rates over a very large portion our target galaxies. With our 3.5m telescope, we will moreover be able to follow the nova light curves almost to minimum, allowing classification of the novae according to their light curve characteristics. Follow-up spectral classification for many of the novae we discover, with WIYN and the INAF Galileo telescope, will assist with this classification.

With these detailed diagnostics, we can eliminate the 15-20% spurious transients that might mimic novae (although these transients can be interesting in their own right; see below). Then, we can establish the incidence rates of the different types of novae — a key step in testing current theories. One of the first results from the FastTING (Fast Transients in Nearest galaxies) survey is that there may be many more T-Pyx type RNe (slow recurrent novae) than previously thought, but they are missed in extragalactic surveys because they are not very luminous at maximum (see Fig. 3.1). This is an interesting possibility that we will certainly be able to explore for M31 and M33.

Although part of our scientific goals can be achieved without the U and Hα filters, these filters are very important for the success of this project, especially Hα. The UW Department of Astronomy and the WIYN consortium have applied to US agencies to obtain the filters as soon as possible. Optical transients, especially classical and RNe, are much brighter in Hα than other optical bands. We will use the broad-band filters instead of an off-band filter to subtract the continuum level and resolve novae spatially (even in most of the nucleus of M31 and M33) and obtain precise positions (this is

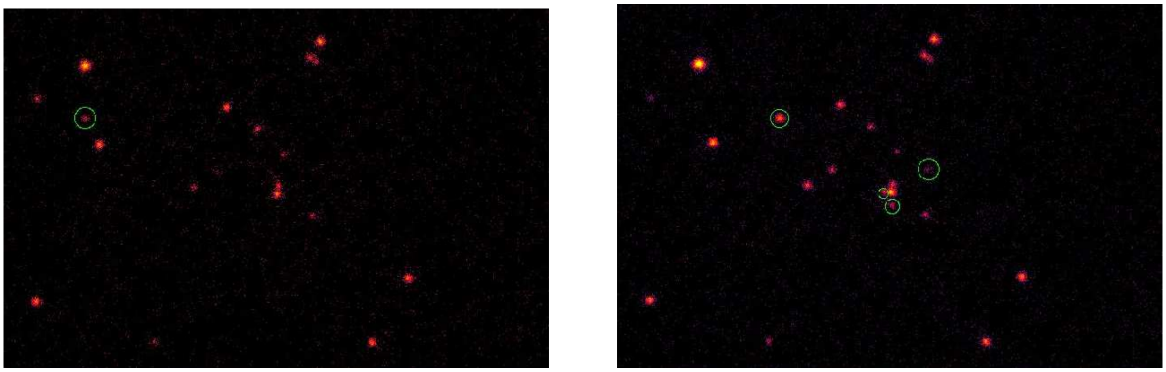


Figure 4: Chandra HRC-I images of the innermost center of M31 (1.5x1 arcminutes) taken on December 2 of 2004 and on February 20 of 2005. The green circles show the X-ray (but also optical!) transients, observed to change every week, and usually identified as classical, recurrent and black-hole novae.

done routinely in extragalactic nova searches). The U-band light curve is also of interest because both the WD and the ejected shell emit in strongly UV (a fact known since the early studies of Gallagher & Starrfield 1976, 1977; see also Orio et al. 2010 for results concerning specifically the novae in M31).

3.1.2 Black-hole Transients

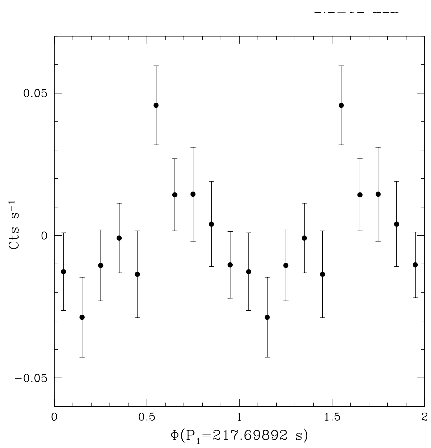
Thanks to regular X-ray monitoring, several X-ray transients are observed every year in M31 and M33. About half are thought to host a black hole. These systems display a simultaneous optical outburst, but the eruption occurs without mass outflows and thus is very different spectroscopically from classical/recurrent novae (e.g. Kuulkers, 1998). The instability that triggers the outbursts is thought to occur in an advection-dominated accretion disk (e.g. Meyer-Hofmeister & Meyer, 1999) and has very dramatic observational consequences, reaching Eddington luminosity in X-rays and with a $\simeq$8 magnitudes amplitude (similar to RNe) at optical wavelengths.

In the past, black-hole binaries in eruption have often been mistaken for novae, although the two can be clearly distinguished both in X-rays (spectra and light curves are totally different for RNe), and in optical spectra (there are no P-Cygni profiles in black holes). To data, tens of candidate X-ray novae have been observed in M31 (e.g., Williams et al. 2005, and Fig. 5), but without coeval optical observations a confirmed identification is not possible.

An accurate rate and classification of black-hole transients in M31 and M33 is thus an interesting and important goal. In the core of M31, where the black-hole transients are most often observed, we should be able to use Hα imaging as with classical and recurrent novae. We are not able to reach HST resolutions in the innermost core, but unlike HST, we can monitor the objects over months to obtain the whole light curve. Optical light curves and spectra (obtained with WIYN/Hydra or with the INFAF Galileo telescope) will differentiate black-hole transients from novae. However, even in the absence of spectra, multi-band light-curves will provide much of the needed information.

3.1.3 The Population of Quiescent X-Ray Binaries (XRB)

About 2000 X-ray sources are known in M31, and 300 in M33. Out of 1460 sources observed with XMM-Newton, about 300 have been found to be variable (Pietsch et al., in X-Ray Astronomy 2009, in press). Some of the M31 fields were only observed once, so the true number may be even higher. We estimate that with WIYN we can reach the optical magnitude of more than 30% of the quiescent XRB. This will offer a uniquely large sample to test evolutionary models for XRB in general, and black hole transients in particular. This research overlaps with co-I Gallagher's involvement in studies of X-ray transients in E galaxies, which can provide X-ray statistics but no optical identifications (Brassington et al. 2008, 2009).



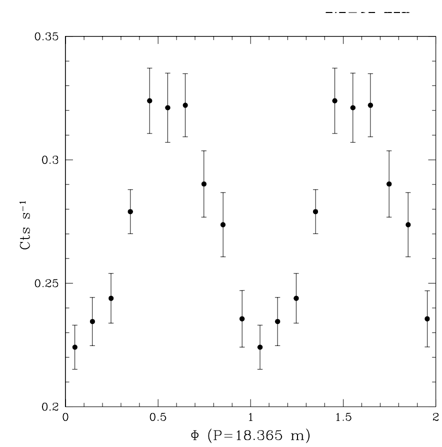


Figure 5: Today stellar astronomy is also extragalactic. The X-ray light curves of two supersoft X-ray sources in M31 that show different periodicities in X-rays: r2-12 (left) of 217 seconds, 18 minutes for Nova 2009 12-b (right). We show these results to demonstrate that variable stars in M31 can be more closely studied that we tend to think.

Together with this overall census, we plan to examine correlations between X-ray and optical variability. Optical monitoring of all XRB detected in M31 and M33 (low mass XRB in outburst, sometimes in quiescence, and high mass XRB in quiescence) is extremely interesting. We will be able to measure the orbital periods of more than half of the known HMXB in our fields; by comparing them with the Galactic and Magellanic Clouds populations of HMXB, we can investigate the effect of metallicity on the formation and evolution of these systems.

3.1.4 Supersoft X-ray Sources

Supersoft X-ray Sources (SSS) are defined phenomenologically as a class of X-ray sources that include hot, accreting and hydrogen burning white dwarfs in binaries. They are a major research focus for PI Orio. SSS are extremely luminous (in the range 10^{36-38} erg/s, thus reaching the Eddington luminosity of a 1 $M_\odot$ star), but the emission peaks in the very soft X-rays or extreme UV, and therefore often suffers strong strong absorption. For this reason, the bulk of SSS are observed in external, nearby galaxies (including and even beyond the Local Group; see Fig. 6) in directions of low N(H). SSS often exhibit extreme behavior, such as X-ray flux variability on time scales of minutes or hours (orbital, white dwarf spin and probably non-radial pulsations). We know that about 50% of SSS are post-outburst novae and recurrent novae, and 20% to 35% turn out to be other types of accreting and shell hydrogen burning white dwarfs in binaries (see Greiner 2000, Orio 2006 and Fig. 5, from Orio et al. 2010).

Both the frequently erupting RNe and the non-novae SSS are very interesting as type Ia SN progenitors. M31 is regularly monitored in X-rays over large fields[1], leading to the discovery of tens of SSS every year. These observations lack the accompanying optical light curves necessary to interpret the mechanism behind the X-ray variability. However, with a large fraction of SSS having optical counterparts that are sufficiently bright to be observable with WIYN, this gap can be closed by the *Living Galaxies* survey — allowing us for instance to understand whether thermonuclear burning in accreting WDs proceeds at a constant rate, meaning that the system is on a path towards a SN Ia.

[1] PI Orio is a co-I in some of the X-ray monitoring programs of M31 and M33, which are likely to be continued by the Chandra and XMM-Newton observatories into the ODI era.

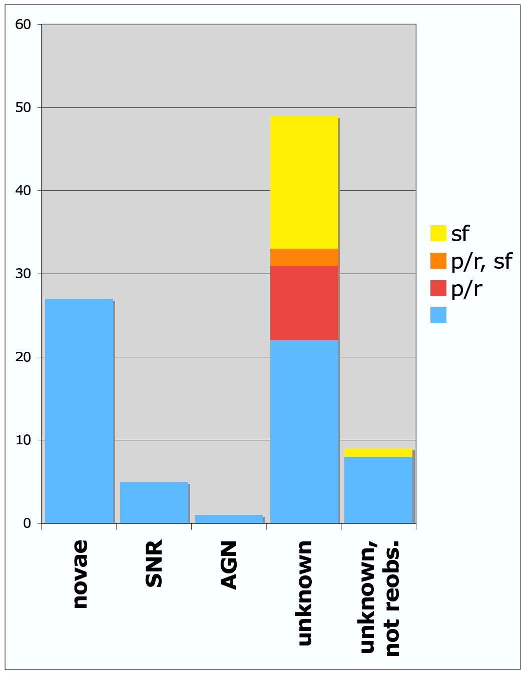


Figure 6: The distribution of SSS in M31 (Orio et al. 2010, submitted to ApJ) in different groups: classical and recurrent novae after an optical outburst, supernova remnants, AGN, still unclassified objects observed multiple times, or observed only once. The unidentified SSS are either associated with old populations, or with star forming regions and OB optical counterparts (yellow and orange stripe). The sources that were re-observed in X-rays turned out to be persistent (few), transient or recurrent (most).

3.1.5 Symbiotics

In symbiotic binary systems a cool star (a red giant) has a hot companion (usually a compact object, mainly a white dwarf), often surrounded by a nebula. When there is a WD, shell H burning often occurs. As mentioned above, there is an overlap between symbiotics and SSS. There is also an overlap between symbiotics and recurrent novae, since symbiotics at times undergo thermonuclear flashes. The compact object accretes material through a wind or even an accretion disk. Some symbiotics are likely progenitors for type-Ia SNe (Hachisu et al., 2008). The statistics, and when possible, determination of the physical parameters of a symbiotics will place constrains on the evolution of these systems and make progress in the study of type-Ia SN progenitors. No symbiotics have been observed and studied yet in M31 and M33, although the discovery of a symbiotic in IC 10 at a $\simeq$700 kpc distance (Fig. 7) demonstrates the feasibility of finding extragalactic symbiotics with Hα imaging and spectroscopic follow-up with a mid-size telescope. We will monitor and measure the orbital periods of these systems, and we may even witness some outbursts and obtain indications of other variable outflows.

3.2 Massive Stars

Massive stars are *galactic feedback engines* — via their strong winds and supernova explosions, they inject huge amounts of energy, momentum and material into their surrounding environments, driving the chemical evolution and star formation of their host galaxies. Throughout their lives, they also weather a host of instabilities that can drive periodic pulsations (e.g., the β Cepheid stars and slowly pulsating B stars), trigger the episodic ejection of equatorial material into a Keplerian disk (e.g., Be stars), and produce eruptive episodes that drive off significant amounts of mass (e.g., Luminous

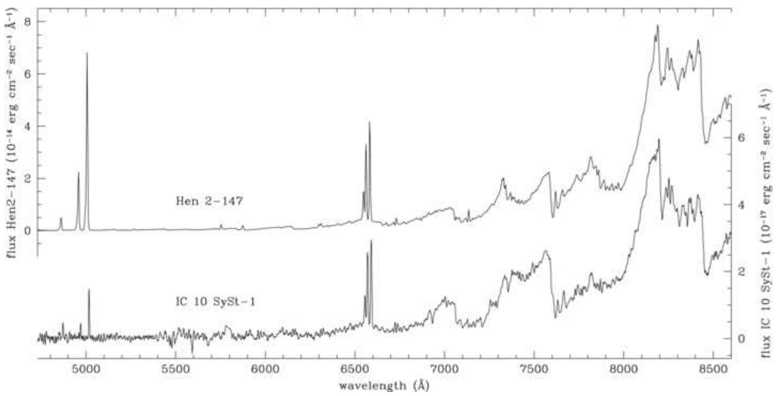


Figure 7: The optical spectrum of the symbiotic star StSy-1 in IC 10, a dwarf irregular and starburst satellite of M31, taken with two gratings and the CMOS-N detector at Gemini North, and comparison with the observed spectrum of the Galactic symbiotic Hen 2-147. See Goncalves et al. (2008) for details.

Blue Variables). These instabilities are intricately linked with the physical processes occurring deep within these stars' envelopes, and thus can potentially shed light on aspects of stellar astrophysics that remain poorly understood.

3.2.1 Be Stars

Be stars are early B-type stars characterized by the appearance (transient or continuous) of Hα emission, presumed to come from an equatorial *decretion* disk. The mechanism for the formation of this disk remains one of the longest-standing mysteries of stellar astrophysics; rotation, pulsational instabilities and even magnetic fields may each play a role. In recent years, with the emergence of evidence that Be stars may rotate very close to critical (see Townsend et al, 2004), there has been a groundswell of interest in these objects as laboratories for understanding the structural and evolutionary effects of extreme rotation.

Unfortunately, 25-50% of Be stars go unobserved in optical surveys, because their disks are not permanent and have very variable structure (McSwain et al. 2008, 2009). Hubert & Floquet (1998) examined the Hipparcos sample of Be stars and found that early-type Be exhibit a very high degree of variability. They also identified 14 Be stars with recurrent short-lived outbursts (0.06$\leq$ Δmag, $\leq$ 0.3 over timescales of 50-500 days) and 8 with long-lived outbursts (Δmag $\geq$ 0.12 over timescales of $>$500 days) in the sample. McSwain et al. (2008) discovered a new Be star (#130) in the open cluster NGC 3766 whose Hα line switched from emission to absorption over a couple of years, indicating the rapid dissipation of its disk.

The *Living Galaxies* survey will allow a representative census of the Be-star populations of M31 and M33, determining the overall incidence rate of the Be phenomenon (and how this might vary with the strong metallicity gradients in M33), and establishing disk formation and destruction timescales. The former will shed light on why the phenomenon manifests itself in some stars and not others; and the latter will help us constrain the physical processes that build and then destroy the stars' circumstellar disks.

3.2.2 β Cepheids

β Cephei stars are massive ($M \gtrsim 8\,M_{\odot}$) main-sequence stars showing periodic light and spectroscopic variations, with typical periods of a few hours and amplitudes up to 0.3 mag. The variability arises from self-excited radial and non-radial pulsations, driven by a κ-mechanism instability operating on a peak in the stellar envelope opacity at temperatures $\sim 200,000\,$K. This peak — often termed the

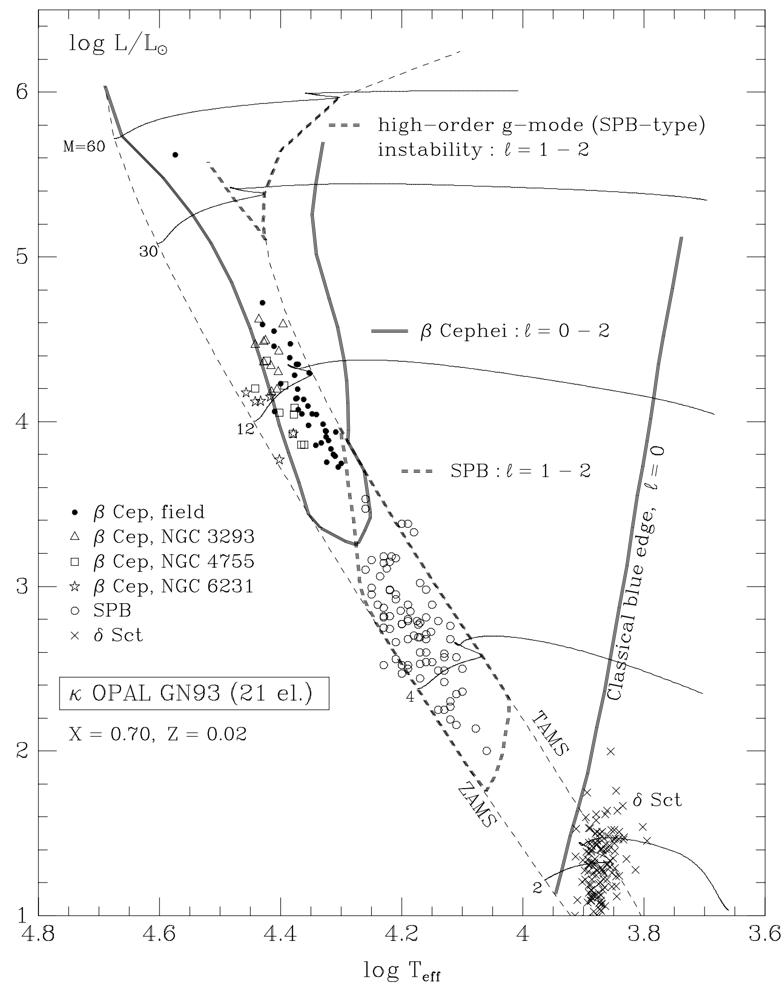


Figure 8: Pulsation instability strips in the upper main sequence, computed using OPAL opacities. From Pamyatnykh (1999).

'iron bump' — arises due to millions of bound-bound transitions of iron and nickel. Fig. 8 shows the regions in the upper part of the HRD inhabited by iron-bump pulsators — both β Cephei stars and, at lower luminosities — slowly pulsating B (SPB) stars. The boundaries of these instability strips are strongly sensitive to metallicity, and therefore surveys of pulsating massive stars are ideal tools for probing abundance distributions and/or testing opacity data.

Extragalactic surveys have so far extended only to the Magellanic Clouds (Sterken & Jerzykiewics, 1988, Pigulski & Kolaczkowski, 2002), because of the high cadences required, and the need for spectroscopic follow-up to weed out objects that mimic β Cepheid behavior. With the *Living Galaxies* survey, we will be able to find almost all high-amplitude ($\Delta m \gtrsim 0.1$) β Cepheids, providing us with the first near-complete censuses of these massive pulsators in regular galaxies.

3.2.3 "V838 Mon"-type Objects

Beautiful HST images illustrate the optical echo of V838 Mon (see Fig. 9), but the nature of this object is really still elusive. Almost certainly this phenomenon is an eruptive stage in advanced high mass binary stellar evolution, but it is still a matter of intense debate and study. A similar eruption

Figure 9: The HST-ACS image of the light echo of V838 Mon, at a distance of about 10 kpc. We know only one such object in M31... how many more of them wait to be discovered?

was already observed once in M31 (see Bond & Siegel 2006 and references therein). Many peculiar variables of this type are probably mistaken for classical novae, because of infrequent monitoring and lack of identified quiescent counterparts, but by closely following the light curves of many variables M31 and M33, since the light curve really is very different in novae and in V838 Mon type variables, we will select candidate optical transients of this type and find out whether they have a binary star with a massive component as quiescent counterpart.

3.3 Companion Projects

3.3.1 Microlensing Studies

Since the original suggestion by Paczynski (1986), microlensing is an established research tool for the detection of compact halo object (MACHOs), a possible dark matter component of galactic halos. Several microlensing campaigns have been undertaken in the last 20 years towards the Galactic centre and the Magellanic Clouds (e.g. Moniez, 2010) and towards M31 (e.g. Calchi Novati, 2010). In particular, towards M31, observational campaigns have been carried out by several collaborations, among which are AGAPE and follow-ups (Ansari et al 1999, Calchi Novati et al. 2005, 2009), WeCAPP (Riffeser et al 2006, 2008), MEGA (de Jong 2006). In addition to offering a database for M31, our survey will be a *unique* resource for microlensing studies in M33. These surveys were carried out with smaller telescopes and field of views than WIYN with ODI. Incidentally, they are useful for our variability study because they offer a long term basis to compare a number of our variables. However, as for the MACHO surveys, all the microlensing results are still controversial. Our survey should offer new, high quality material for these studies. co-I Calchi Novati is PI of the PLAN collaboration, and is enthusiastic at the idea of becoming our link to ensure that our database is exploited properly for microlensing searches.

3.3.2 Classical Cepheids

There have been recent attempts to better determine the distance to M31 and M33 through the period-luminosity relation of classical Cepheid pulsators (Vilardell et al. 2008), but the dependence of the stars' light curves on metallicity still needs improvement. This is of course a fundamental problem in astronomy, and one to which our data will contribute essential information.

3.3.3 Eclipsing Binaries

We will obtain excellent light curves for the most luminous eclipsing binaries of M31 and M33, to be used to refine distance determinations (e.g. Todd et al. 2005, Vilardell et al. 2006). Since this will be carried out with the same data sets used for the Cepheids, it will allow an accurate inter-comparison of the derived distances without the uncertainties associated with photometric calibrations.

3.3.4 Deep Hα Imaging

Figure 10 shows a beautiful image of one of the M31 fields, obtained by co-I Gallagher with WIYN and Mini-MO. Figure 2 illustrates the comparison with 4m NOAO telescope and the LGS. Although the *Living Galaxies* survey has many components that can be done with broad band filters, Hα is the most interesting in many respects. It will be essential for a quick and precise recognition of recurrent and classical novae and it will allow to map virtually all symbiotics in the rich population of Andromeda and the Triangulum. Wide field deep images in this filter also open up a series of possibilities that go beyond our original goals.

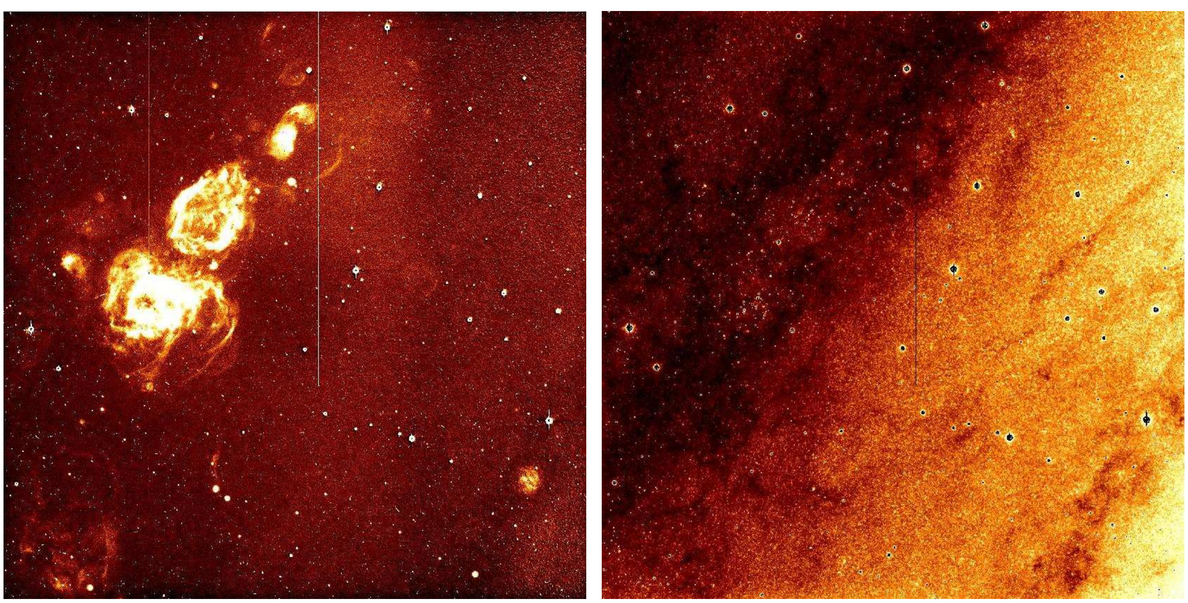


Figure 10: A field of M31 imaged in Hα by Gallagher with the WIYN Mini-Mosaic in a 15 minutes exposure. The Hα image after subtraction of the normalized R image is shown on the left, and the original R image is on the right. The R-image subtraction procedure allows faint structures to be resolved in detail.

Class of sources	Time scales	Cadence	Variation amplitude	Filters
Classical novae	1 year	weekly monthly	$8-17$ mag (steady decrease)	g, r, i,Hα U
Recurrent novae	$2-9$ months	weekly monthly	8 mag (steady decrease)	g, r, i,Hα U
Symbiotics (in outburst)	< 6 months	weekly monthly	$8-10$ mag	g, r, i,Hα U
Symbiotics (quiescent)	$1-5$ years	monthly	0.1 mag (oscillation) ≥ 0.1 mag (orbital)	g, r, i r, i
SSS (bright phases)	$1-3$ months	weekly	≥ 0.05(irregular)	g,U, Hα
Microquasars	$2-8$ months	weekly	$7-8$ mag	g, r, i,Hα
β Cepheids	$2-17$ hours	daily for> 4 hours	≥ 0.1mag (pulsation)	g, r, i
Microlenses	$1-21$ days	daily	≥ 0.05(oscillation)	g, r
LPV LPV (blue)	> 80 days few days	bi-monthly daily	≥ 2.5(orbital) ≥ 0.05(orbital)	g, r, i g, i
Be stars	> 50 days > 500 days	monthly bi-monthly	≥ 0.05 ≥ 0.12	g, r,Hα g, r,Hα
HMXB	$1-3$ years	monthly	≥ 0.1 mag (orbital)	g,U
Cepheids	$5-200$ days	once/2days	≥ 0.2 mag (pulsation)	g, i

Table 1: Types of variability of the major classes of variable systems and events we will observe, variability timescales and useful filters

4 Observing Plan

The characteristic variability timescales of our targets extend over two or more orders of magnitude (see Table 1; thus, the observational cadence must be chosen carefully in order to ensure that all relevant timescales are adequately sampled. We plan to achieve this by beginning with a short cadence ($\lesssim$ hours), and then progressively lengthening the cadence as the survey progresses. This addresses the sampling issue, and at the same time allows the project to be scientifically productive from the very start (since data for the shortest-timescale objects, e.g. β Cepheids, will be available within the first week).

A significant constraint on the observational planning is that it must fit within the telescope scheduling. UW-Madison will have at most five consecutive nights when M31 and M33 are at low airmass. Around this time of the year (**when?**) the weather can be very variable, and seeing is also not excellent for the whole night. Our plan is therefore to observe M31 and M33 all night for 2–3 consecutive nights, and then follow on with 5–8 *half* nights during the period of longer visibility of the galaxies. The half nights must be scheduled as consecutively, or closely spaced, as possible. During the rest of the year, our analysis of Table 1) indicates that about 1–2 hours of observing time per week would be optimal. We expected a S/N=10 for 23rd mag with an exposure time of .. in ... filters respectively.

In planning total exposure times, we must account for the length of the Hα observations, with an exposure time of about 15 minutes. Because of the many gaps in the ODI camera, the optimal strategy is to dither each exposure with 8 short sub-images. The decision on how often to dither will be made once the characteristics of the instrument are better known. At the moment the overhead time is not exactly known, but with 8 sub-images per exposure, the total overhead can be expensive and has to be accounted for, to achieve the best possible planning. We know that we will need about 30 seconds for acquisition, and *possibly* a minute of total time for each move, depending on some characteristics of the electronics, reaching a total 8 minutes of overhead time for each set of dithered observation.

With the dithering and overheads, the short (1-5 minutes) broad band exposure will be relatively time consuming and need to be planned accurately, possibly ruling out the dithering for part of the nights. Our co-I Daniel Harbeck at WIYN is the ODI Project Scientist, and with him we will refine the strategy to adopt during the verification phase of the instrument.

We are currently exploring contingency plans to maximize the science in case of missed observations due to weather and technical problems. The other significant outstanding question concerns the mode in which the observations will be undertaken. At this time there is no general users' queue set up for ODI. During the UW-Madison nights, we will be able to share time with the ODISSE survey (PI Barger), and with other observers. However, UW may benefit from buying time from the Yale University's survey queue. Another possibility we are investigating is remote observing, already set up from Wisconsin for other WIYN instruments.

Weekly monitoring, whenever possible, in at least two filters for $\simeq$7 months a year is an essential component of our project, a winning strategy for many goals. The two filters are necessary to distinguish source classes. Fig. 3.1 indicates that a weekly cadence is necessary to detect the novae, recurrent novae and other transients that are the most interesting to us: high mass white dwarfs, possibly on the path to SNe Ia explosions (the amplitude and speed class of the thermonuclear outburst is inversely proportional to the mass) and of course black-hole transients. *Thus, for the success of this project a strategy should be in place for some mode of queue or remote observing that allows repeating short observations for many nights during the year.*

5 Previous Surveys of M31 and M33

Both M31 and M33 have been surveyed photometrically with great precision in the Local Group Survey (Massey et al. 2006). The M31 population has been also measured in the Sloan Survey. We will thus have a fixed epoch reference obtained a few years before the *Living Galaxies* survey, and we will be able to judge the quality of our photometry and improve it, when and if necessary.

An additionally external project relevant to us is the large Panchromatic Survey of M31 planned as an HST Treasury project. In the area covered by HST, the spatial resolution and the quality of the HST images will be invaluable for the variability study of our WIYN exposures, because they will give us a high resolution template for deconvolving WIYN images when variable targets are situated in crowded regions.

The HST Panchromatic Survey includes ultraviolet filters. The ultraviolet images of this survey, when they become public, will allow quick identification and astrometry of variable sources when the field is too crowded to identify the correct optical counterpart of SSS and some other types of XRB, or when the source is too faint for detection with other filters. Once we know the existence of a counterpart that we think will likely show orbital variability, a method like pixel imaging with ODI will give the necessary information with optical filters.

6 ODI Amongst its Peers

Although wide-field cameras are becoming increasingly common on intermediate- and large-size telescope, ODI at WIYN has unique strengths that set it apart from its competitors. In the Northern hemisphere, the most comparable facility is the 3.6m Canada-France-Hawaii Telescope (CFHT) with the MegaCAM imager. However, their best angular resolution is poorer than ours, and their field-of-view in Hα, covering 42x28 arcminutes^2, is substantially less than the full one square degree. Moreover, being a multinational-level facility and supporting a wide array of popular instruments, the opportunities to undertake high-cadence surveys with CFHT/MegaCam are quite limited.

The Palomar Transient Factory (PTF) — the 1.2m Palomar telescope with an 8 square degree imager, supported by the 1.5m telescope for some light curve measurement (Law et al. 2009) — is better suited than ODI at finding transients across the full sky. However, it is a poor choice for intensive monitoring of individual clusters or galaxies; it cannot resolve transients anywhere near galactic centers, and does not use Hα filters. Nevertheless, we aim to collaborate with the PTF team in optimizing our observational plan (§4).

Looking now to the future, the 8m Subaru telescope will soon be equipped with Hyper-Suprime Cam, a one degree imager (**check**) which *will* have an Hα filter; however, this facility is dedicated mostly to distant objects and cosmology, and is not expected to be a monitoring survey instrument.

The Pan-STARRS survey, employing (ultimately) four 1.8m telescopes equipped with the same Orthogonal Transfer Array (OTA) CCDs used by ODI, will be dedicated to studies of optical transients and variability in external galaxies. No plans exist for use of an Hα filter, and at present the limiting magnitude (for given S/N and length of exposure) is 1.5 mag shallower than that that achievable with WIYN. Moreover, it seems unlikely that Pan-STARRS can achieve an image quality of $\leq$0.8 arcseconds.

In the Southern hemisphere the Large Synoptic Survey Telescope (LSST), scheduled for completion in 2016–2017, will be much more effective than WIYN in terms of etendue (FOV x collecting area area). The information that will be obtained by LSST on the variable stars of the Magellanic Clouds and other nearby galaxies' populations (e.g. IC 101, NGC 6822) will be an invaluable comparison to the Northern-hemisphere data from the *Living Galaxies* survey.

7 Data Management and Analysis

After the pipeline reduction provided by the University of Indiana ODI data center, the initial analysis of the *Living Galaxies* images will be undertaken by a post-doctoral collaborator (to be recruited, possibly in common with the ODISSE project). Co-I Calchi Novati will provide guidance here, having significant past experience with microlensing projects and, specifically, *Pixel Imaging Software*. Another type of package we may want to use is *Difference Image Analysis* (DIA) software. Both types of software allow detection of variability at low levels, even in non-resolved images (e.g. the inner $5''$ from the center of M31, and about $3''$ from the center of M33, regions that appear flooded with diffuse light in the WIYN exposures). Given the copyright/licensing restrictions of the microlensing software, we plan to train the post-doc to analyze all the images as they are obtained. This will allow us to detect and locate variability as well as measure accurate photometry in "stamp like" sub images around the variables. Only in the most crowded core areas of a few arcminutes will accurate photometry not be possible; however, some spatial information, and the possibility of measurements, will remain in our Hα images.

Full photometric pipelines will be established later in the project, to set up a *Living Galaxies* archive for posterity. We have made initial contact with a colleague (**who?**) at Padova who has worked with the Terapix collaboration, and are already exploring optimal ways the archiving can be achieved. The Terapix group provides imaging and pipeline processing software to the CFHT MegaCAM and their (available) WiFIX software is of course of interest for ODI.

8 Spectroscopic Follow-up

Spectroscopic identification and follow-up will be an important part of the *Living Galaxies* survey, especially for transients and for the identification of new symbiotics (see Fig. 7. The Hydra spectrograph of WIYN will be available to us, making a large part of this project self-sufficient without relying heavily on external facilities. In addition we will apply for time on the Padova-Asiago 1.2m and 1.8m telescopes and on the TNG-INAF 3.5m telescope and the SARG spectrograph. The INAF Galileo telescope is very similar and yet very complementary to WIYN — with a smaller field of view, it offers a high-efficiency spectrograph. The novae in M31 during outburst are in the V=15–18 range, and TNG can follow them spectroscopically during the early weeks/months of the decline. We intend to develop a collaborative spectral follow-up program and make it part of the *Living Galaxies* survey; in this respect, our co-Is from Padova are leading experts in spectroscopy of novae and also of symbiotics, and are already engaged in a spectroscopic survey of M31/M33 novae.

Spectral are critical for assessing the physical nature of transients. For example, Di Mille et al. (2010a, 2010b) have already been able to weed out a spurious object (a WZ Sge variable in the M31 foreground) using their first collection of nova spectra. Much of the spectroscopic nova project is based on the behavior of Galactic and LMC novae described by Williams (1992). Williams classified novae near visual maximum in two spectroscopic classes, determined by the relative strength of the non Balmer lines of Fe II, He, and N. Novae with FeII lines show a lower level of ionization and P Cygni profiles. Novae with strong He/N lines show a higher level of ionization and the lines are mostly flat-topped. Following this classification, Della Valle & Livio (1998) found that He/N novae tend to concentrate close to the Galactic plane and are fast and bright, while Fe II novae are slow and faint and are distributed up to $z \sim 1000$ pc and beyond. No RNe have been observed to belong to the Fe II class. Recently Di Mille et al. (2010) used spectra in the literature and new observations obtained at Asiago and at TNG (Fig. 10, 11) to analyse the spatial distribution of the different classes of objects in M31 . Their results do not show a striking difference between the distribution of He/N an FeII novae but they stressed that to correctly weight statistical biases a complete spectroscopic classification of a much larger number of the M31 and M33 novae is very important to constrain the theory.

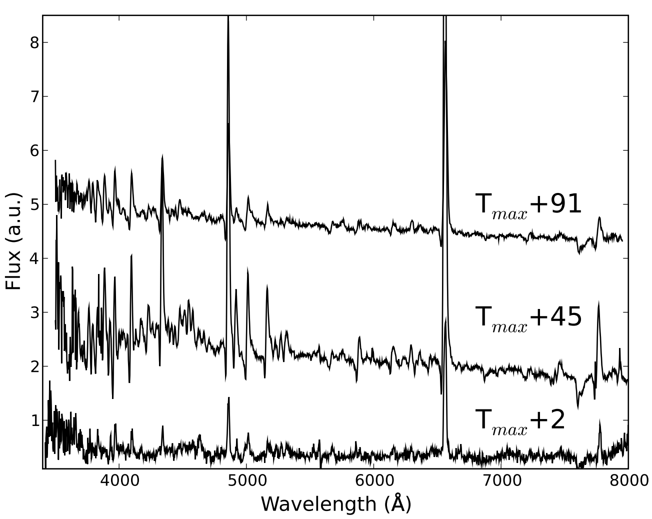


Figure 11: TNG spectra of nova NM31-2008-10b at different epochs

9 Project Team

In addition to co-PI Townsend, our co-Is among faculty members at Wisconsin are Professors Jay Gallagher (stellar populations and galaxies) and Sebastian Heinz (black holes and compact objects in general). A co-I in the project is Dr. Daniel Harbeck, ODI Project Scientist. Dr. Patricia Knezek has expressed interest. Several other INAF colleagues of Orio are interested in collaborating with the *Living Galaxies* survey in their areas of expertise.

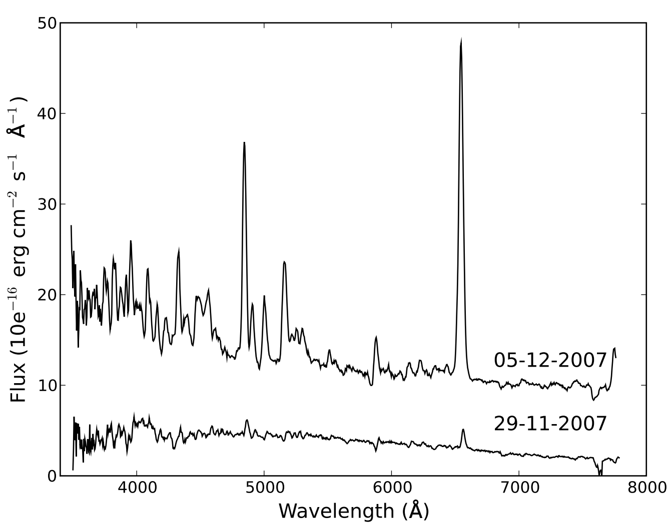
We already have several Italian collaborators associated with the the Italian Institute of Astrophysics (INAF): Drs. Iijima and Siviero (INAF Padova), Dr. Calchi Novati (Salerno University), Dr. Di Mille (Magellan Telescope and Padova University), Profs. Bianchini, Ciroi, and Rafanelli (Padova University). Letters of interest have also been received from Dr. Ginevra Trinchieri (INAF-Milano, XRB populations in external galaxies), Dr. Domitilla de Martino and Dr. Massimo Della Valle (INAF-Napoli, cataclysmic variables, novae outbursts, black hole candidates), and Drs. Ulisse Munari (INAF-Padova, symbiotic stars and novae). The research team of Prof. Scarpetta, with which Calchi Novati works in Salerno, has expressed interested in in studying the microlensing events in our exposures, on behalf of the PLAN microlensing international collaboration. In parallel we expect also to have collaborators from the massive stars and Be-star communities, and we will develop these links once the timeline and ODI capacities become clearer.

10 Timeline

During the science verification phase of ODI we will analyse technical and organizational problems that are difficult to solve before having access to the data in their final format. We still cannot gauge exact overhead times, which may be as short as the 30s acquisition time if the telescope can move without significant electronic noise, or almost twice as long. This will have impact on how many dithered images we decide to obtain. We will also learn how to use the variability software on the ODI images and continue the collaboration with the Padova Astronomy Department on the M31 and M33 nova spectra, already before many new novae are discovered by ODI, as a scientific foundation for interpreting results from the nova database we will acquire.

The following is unedited, and needs tidying up....

Figure 12: NM31 2007-11c spectra at Asiago Observatory



As soon as ODI is fully operational we plan to analyse the data to obtain rates of novae, recurrent novae and transients with black hole candidates. After the first year we would like to publish some "early science": rates of these three types of events, especially the nova rate, with a spectroscopic library of support for classification.

One of our first goals is also to identify symbiotics for the first time in M31 and M33, which can be spectroscopically distinguished from planetary nebulae, and obtain a picture of the M31 and M33 symbiotics population, which then we can compare with the type Ia supernova rate.

We plan this survey as a five years project. Three years is the minimum length of time we think we need to achieve completeness in some areas of this research, such as the study of transient Be stars, and microlensing candidates, which must be distinguished from the other eruptive variables.

Initial requests of funding for a preliminary phase of accurate preparation have been submitted to NSF in the context of a general proposal on X-ray binaries, and to INAF on the side of the Italian collaboration. We are aware that the *Living Galaxies* survey will require the dedicated work of a post-doctoral scientist, and hope to obtain some funding to hire such a precious collaborator.

We would like to stress that early acquisition of an Hα filter, and definition of a queue or remote observing mode to obtain weekly monitoring observations, are essential for the success of the project.

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