THE LIVING GALAXY

A survey project with ODI at WIYN

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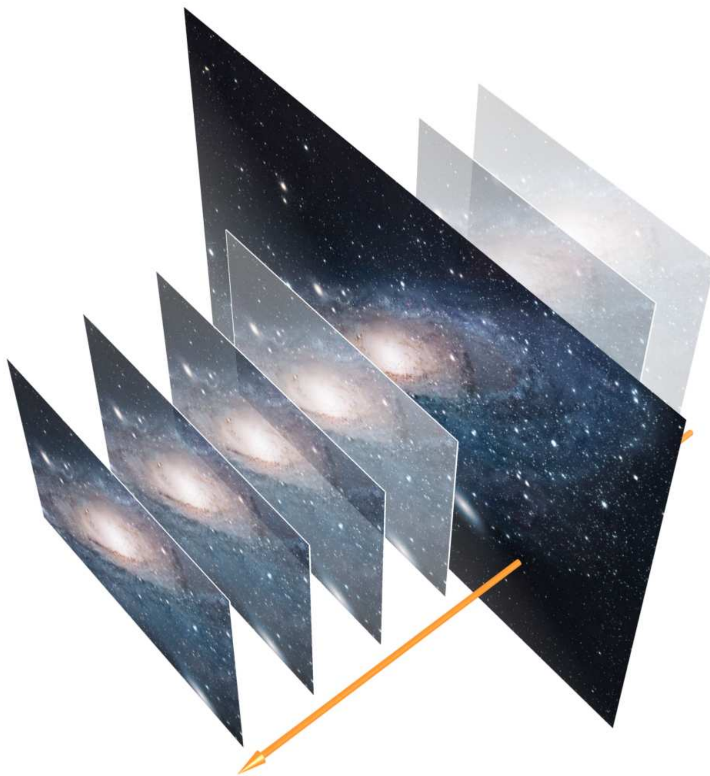


1 Abstract

We propose a time monitoring survey of the North-East quadrant of Andromeda and all the Triangulum galaxy with the WIYN One Degree Imager (ODI). It will be the first systematic study of optical variability of the two galaxies, with four filters, including the narrow band Hα. The sampling time scales will be minutes, hours, days, months and years. Our central science drivers are the following: obtain a full picture of compact object binaries in outburst, including rates of different classes of novae and black hole transients, derive statistics and basic parameters of quiescent symbiotics and high mass X-ray binaries, study massive star variability, like β Cepheids and flaring Be stars, and acquire a database useful for the study of long period variables and microlensing. This project will be a legacy and a reference for the study of variable stars populations for many years to come, and will also yield the deepest Hα exposures ever obtained for M31 and M33.

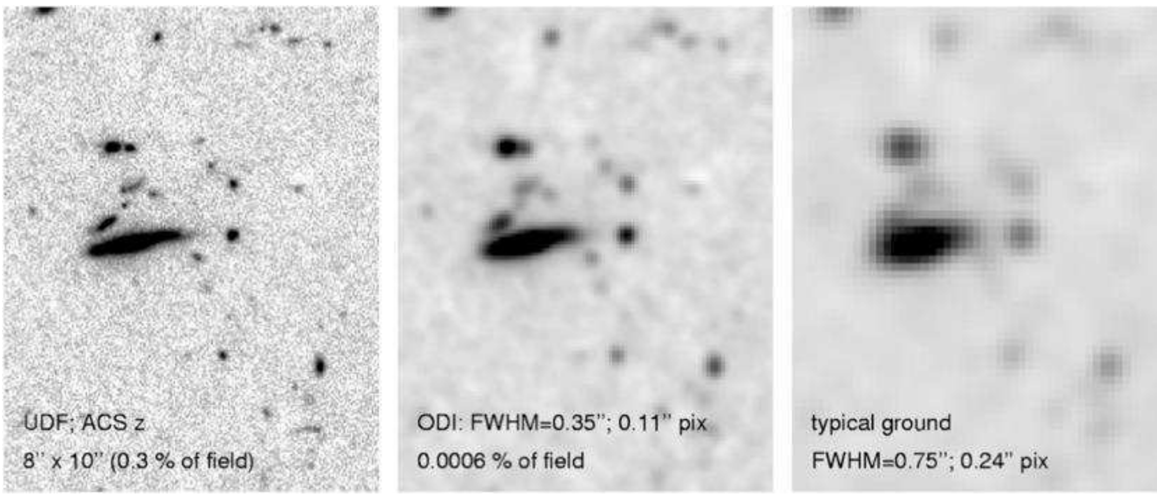


Figure 1: Comparison between an HST ACS image, and the same image degraded to ODI best quality (middle) and best quality of the 4m telescope at Kitt Peak.

2 Scientific Goals

Variable stars led humans to pay attention to the "divine signs" in the sky and fostered people's curiosity about the Universe. In our 21st century, the next decade is going to be the epoch of large astronomical *surveys*, and of *high resolution*. Spectral and spatial resolution are both improving at a fast pace with the current instruments, but the time resolution is improving even more rapidly. 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. We propose to bring the wide field imager of a mid-size telescope with excellent optics into the *time domain*.

By regularly monitoring rich and varied stellar population over one degree fields we will explore the parameter space of close binaries undergoing mass transfer, and of massive stars instabilities. Massive stars and accreting binaries are two topics of excellence in Wisconsin, in which we have knowledge and expertise. Transient, eruptive objects among these two classes of objects will constitute a main component of the *Living Galaxy*. In addition, our database will be invaluable for microlensing studies, of interest to several international research groups and to one of our external collaborators. Our co-I Calchi-Novati is an expert of software used to identify variability in large datasets, and therefore brings also a precious contribution to the project. We will also be able to measure the light curves of Cepheids and eclipsing binaries for accurate distance determinations and evaluation of the metallicity-standard candle relationship. Finally, since we will use Hα images to pursue our scientific goals, we will obtain the deepest and most complete Hα maps of these galaxies, which will be an important legacy of the *Living Galaxy.*

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 Section 5 we briefly explain what photometric reference is available to us, and in Section 6 we make the case for ODI to pursue this particular project by showing how it is competitive in the "realm" of wide field imagers. Section 7 contains some plans on data analysis and management, in Section 8 we discuss the spectroscopic follow up. Finally, we outline the scientist involved and growing collaborations and sketch the time line of the project in Sections 9 and 10, respectively.

3 Variable stars: The astronomy of the last millennia in an innovative project of our days

Our knowledge of the Local Group stellar populations has been greatly expanded in the last years, thanks to high resolution imagers with larger fields at ground based telescopes and to the Hubble. The metallicity dependence of distance indicators like RR Lyrae and Cepheids has been studied in several galaxies, and H-R diagrams of extensive regions of Local Group galaxies are revealing the history of star formation. ODI on WIYN, a one degree field detector with scheduling flexibility and a substantial number of nights per year allocated to the UW, wll give the unprecedented occasion to improve also the study of the interacting binaries population, a necessary ingredient to understand the distant universe. Fig. 1 shows the typical spatial resolution of ODI, compared with other ground telescopes and with HST. Although clearly we cannot compete with HST resolution, we have instruments that obtain the best results from the ground, and are excellent for the study of resolved stellar population in nearby galaxies.

Methods and software packages have been devised in recent years to study variability even in non-resolved stellar population. This is something we will definitely want to do in 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 distance from the core these rapid methods of image comparison allow to detect 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, which is comparable for M33, implies that we will observe a very large number of optical transients in outburst, and quiescent variable phenomena involving 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 with a compact object, and obtain an optical variability database even for a large number of different astrophysical objects. Our project will overlap in time with Swift, XMM-Newton and Chandra monitoring observations of M31 and M33 in the UV and X-ray, wavelength ranges 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 parameters of the physics of these transient objects. In addition the recently approved Multi-Cycle Treasury HST project on the North-East quadrant of M31, the same chosen by us, will yield superb reference images at one epoch in several filters, including the UV, a range in which many cmpact binaries are luminous and crowding is dramatically reduced.

Among massive stars, β Cepheids are very luminous objects but because of the long observations needed, they have not been studied well in external galaxies. The metallicity dependence of these objects is not well known, yet they are powerful distance indicators because of their intrinsic luminosity. Another important target are Be stars. They display large variability and flares that are still poorly studied, and are of interest also to better understand high mass X-ray binaries.

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 currently also takes part in a project of spectroscopic classification of the M31 novae, done 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) which has already yielded deeper and better photometric images than the Local Group Survey (see e.g. Fig. 3). Fig.4 shows a comparison of one of the quality of the of the images with the Local Group Survey done with the KPNO 4m telescope (Massey et al. 2006, 2007). Accreting systems can

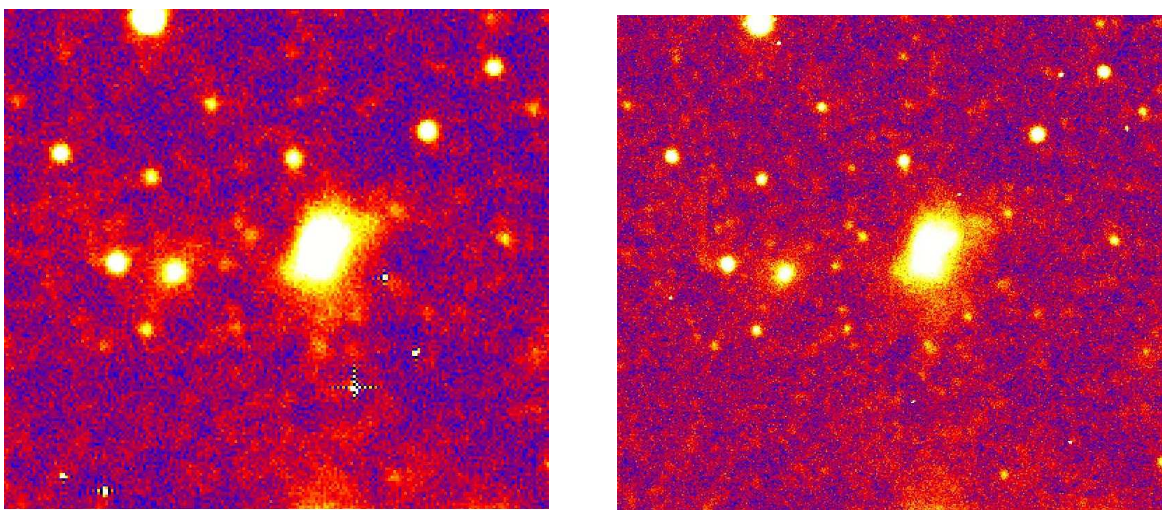


Figure 2: A detail from one of the miniMO Hα images, in a 0.8x0.95 arcmin area, is shown on the right while on the left we show the comparison with a public LGS image of the same region. The LGS image was obtained in a 5 minutes exposure at the 4m Kitt Peak telescope with the same filter we used.

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.

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. Because of a selection effect concerning the frequency of the outbursts on more massive WD, Novae are also excellent indicators of the star formation rate history of a galaxy: the outburst recurs more often in systems containing high mass WD, 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 FOV (e.g. Darnley et al. 2006, Fliri et al. 2006, Heinze et al. 2008). Novae

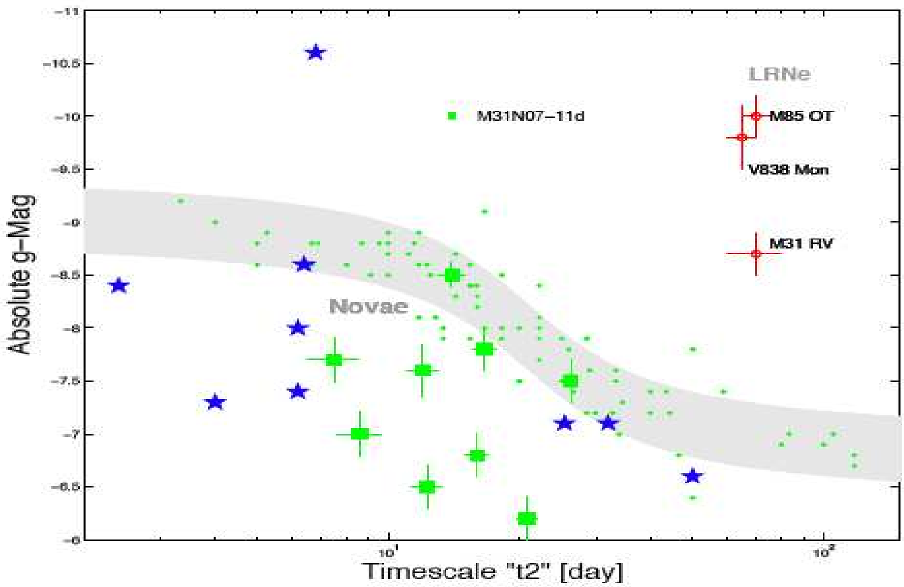


Figure 3: The green squares are putative novae observed in external nearby galaxies by the FastTING team (courtesy of Shri Kulkarni and Mansi Kasliwal). The small green dots in the magnitude versus time for a 2 mag decay are the classical Galactic novae used to calibrate the Maximum magnitude Rate of 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.

in our Galaxy appear to be mainly a bulge population, heavily effected by absorption. In contrast there is very little intervening gas to the core of M31 and inside the core itself. The nova rate in M31, an Sb spiral (the most updated value seems to be 65 year^{-1}, Darnley et al. 2006), normalized to the luminosity, appears to be much higher than in M33, which is a Sc. The estimates for M33 vary between 2 and 5 year^{-1} (Sharov 1993, Della Valle et al. 1994, Williams & Shafter 2004). This difference has been interpreted as an indication that novae are mainly an old population and seems to be confirmed by 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 angular size of M31.

While all authors have extrapolated the nova rate measured in small fields to all the different regions of galaxies with different metallicity and star formation history, we will measure precise rates over a very large portion of both galaxies. Because we use a 3.5m telescope, we will also follow the nova light curves almost to minimum and classify novae according to their light curve characteristics. In addition, spectral classification, repeated even at different epochs, will be done for many novae of our sample, with WIYN and with the Galileo telescope of INAF, which is similar to WIYN, but offers medium and high resolution slit spectroscopy. Studying novae in more detail we will eliminate the 15-20% spurious transients, interesting in their own right (many of them are black hole transients). Most important, we will also constrain the nova theory by indicating the rates of different types of novae, including RN (novae that recur on the scale of a human lifetime and are thought to occur on very massive white dwarfs). One of the first results of an initial precursor of the PTF survey, the FastTING (Fast Transients in Nearest galaxies) is that there may be many more T-Pyx type RNe

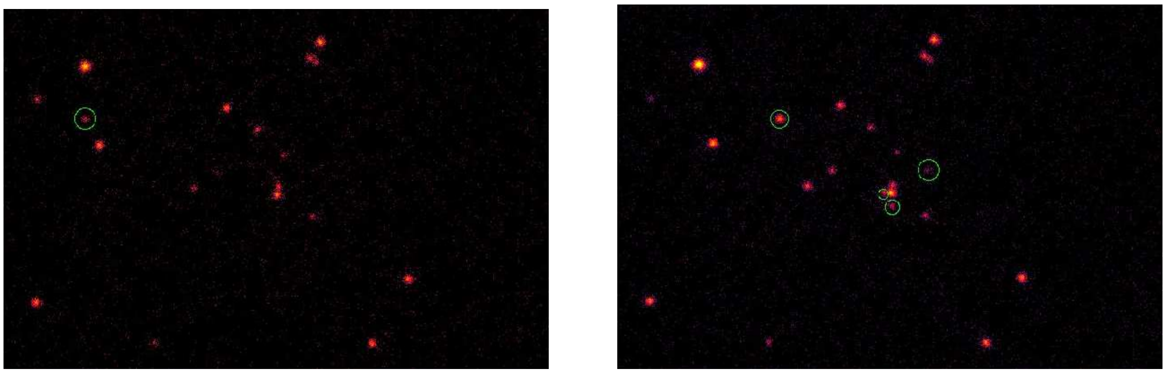


Figure 4: Chandra HRC-I images of the innermost center of M31 (1.5x1 arcmin) taken on December 2 of 2004 and on February 20 of 2005. The green circles show the X-ray (but also optical!) transients, observed to change every week, and usually identified as classical, recurrent and black-hole novae.

(slow RNe) than previously thought, but they are missed in extragalactic surveys because they are not very luminous at maximum (see Fig. 5). 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 (44cm in size, with a a cost of about $80,000 each), 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 them as soon as possible. Optical transients, especially classical and recurrent novae, are much brighter in Hα, and 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 done routinely in extragalactic nova searches). The U lightcurve is also of interest because both the WD and the shell emit in 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).

Black hole "novae" in outburst: Thanks to regular X-ray monitoring, several X-ray transients every year are observed in M31 and M33. About half of them are thought to host a black hole. These systems display a simultaneous optical outburst. but the eruption occurrs 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 there are two ways of discriminating very clearly: the X-ray observations (spectra and light curves are totally different for recurrent novae), and the optical spectra (there are no P-Cygni profiles in black holes). By now, tens of candidate X-ray novae have been observed in M31 (e.g. Williams et al. 2005, ApJ, 620, 723, and Fig. 6) but without optical observations done around the same time (only the very central core of M31 has often been monitored with HST), the information is not complete. An accurate rate and classification of black hole transients in M31 and M33 is thus is an interesting and important goal. Even in the core of M31, where the black hole transients are most often observed, we should be able to use Hα imaging like for classical and recurrent novae . We are not able to aim at the HST resolution 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 the WIYN Hydra or with the Galielo INAF telescope) will differentiate black-hole transients from novae. However, in absence of spectra, a multi band lightcurve will provide much of the needed information.

The population of quiescent X-Ray Binaries (XRB): About 2000 X-ray sources are known in M31, and 300 are known 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 observed M31 fields were not observed again, so the true number may even be much higher. We estimate that with WIYN we can reach the optical magnitude of more than 30% of the quiescent XRB, measuring even a significant number of orbital periods. This will offer a uniquely large sample that will tst 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).

In addition, we want to be able to correlate 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 known HMXB in our fields and compare them with the Galactic and Magellanic Clouds population of HMXB, investigating the effect of metallicity on the formation and evolution of these systems.

Supersoft X-ray Sources (quiescent, or during flares): Supersoft X-ray Sources (SSS) is a phenomenological definition of a class of X-ray sources that include hot, accreting and hydrogen burning white dwarfs in binaries which 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 is peaked in the very soft X-rays or extreme UV, which are easily absorbed. For this reason, the bulk of SSS are observed in external, nearby galaxies (even outside the Local Group) in directions of low N(H). SSS show amazing properties, including X-ray flux variability on time scales of minutes or hours (orbital, white dwarf spin and probably non-radial pulsations) studied even at M31 distance (see Fig.6). 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 recurrent novae and the non-novae SSS are very interesting as type Ia SN progenitors. At quiescence, at the distance of M31 the luminosity of non-novae SSS may vary and have average magnitudes anywhere between 18th and 27th, ranging from symbiotics hosting a luminous AGB star to nova-like, short period systems. In addition, SSS repeatedly observed in X-rays have been only very sparsely observed in the optical, and their X-ray flares have not been followed optically. We are left wondering whether the large X-ray variability is due to cooling of the envelope (corresponding to a brightening in optical, anticorrelated to the X-rays) or to a small scale thermonuclear flashes without mass ejection (X-rays and optical luminosity would be correlated). Understanding flare modes has important implications for the WD mass evolution, and thus is connected with the SNe Ia progenitor problem.

Tens of SSS are discovered n M31 every year. A large fraction of the optical counterparts of quiescent SSS is sufficiently bright to be observable with WIYN. The relationship between the variations of optical versus X-ray luminosity is essential to constrain the theory: M31 is regularly monitored in X-rays over large fields, but the optical light curve is missing at present. The *Living Galaxy* will allow us to understand whether thermonuclear burning proceeds at a constant rate and the system is on a path towards a SN Ia. 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. The SSS that were re-observed in X-rays turned out to be persistent, transient or recurrent X-ray sources.

Making use of X-ray, UV and optical images, in Nelson's 2009 PhD hesis at the UW we found that SSS either associated with old populations, or with star forming regions and OB optical counterparts. The latter are possibly Be+white dwarf systems, and in fact a classification as high mass XRB (HMXB) has been suggested by us (Orio et al. 2010, yellow and orange stripes in the Fig. 5 histogram). If we can prove that they are HMXB, they would explain the time dependent, star formation dependent component in the type Ia SNe rate. We do need optical lightcurves for a more complete characterization.

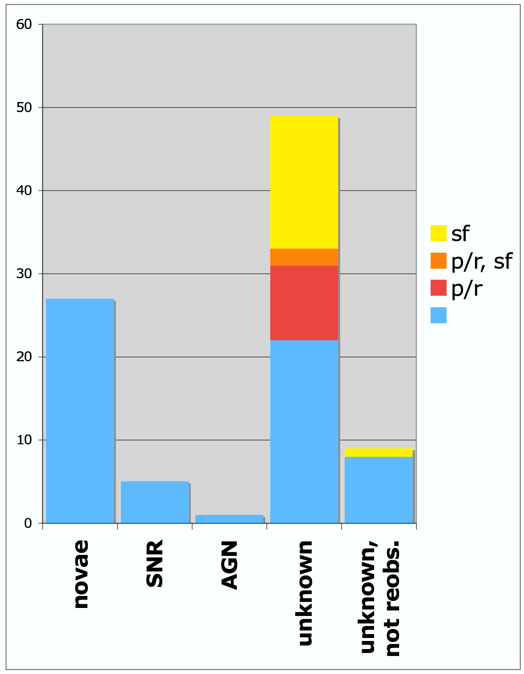


Figure 5: The distribution of SSS in M31 (Orio et al. 2010, submitted to ApJ) in different groups: classical and recurrent novae after an optical outburst, supernova remnants, AGN, still unclassified objects observed multiple times, or observed only once. The unidentified SSS are either associated with 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).

Symbiotics: In these binaries 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 to end type Ia SN progenitor (Hachisu et al., 2008). The statistics, and when possible, determination of the physical parameters of a symbiotics will allow to constrain 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 ≃700 kpc distance (Fig. 7, see Goncalves et al. 2008 for details) proves how feasible it is to find 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: a comprehensive picture

Reaching optical magnitude ≃23.5 or slightly higher with reasonable completeness, we should have a complete picture of stars down to absolute magnitude ≃-1. In addition, summed images (at different epochs, renouncing the information on variabilty) will allow us to reach 2 magnitudes below this level in low stellar density regions.

The main sequence **B stars** cover the stellar mass range responsible for most of the UV light and element production from SNe II in galaxies. Understanding the peculiarities among B stars, and

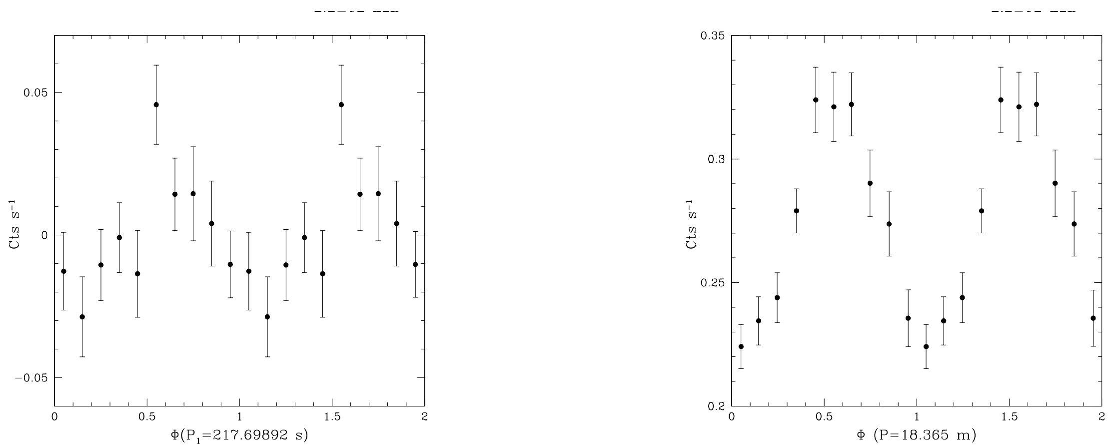


Figure 6: Today stellar astronomy is also extragalactic. The X-ray light curves of two supersoft X-ray sources in M31 that show different periodicities in X-rays: r2-12 (left) of 217 seconds, 18 minutes for Nova 2009 12-b (right). We show these results to demonstrate that variable stars in M31 can be more closely studied that we tend to think.

especially the emission line **B-e stars**, is thus very important. 25-50% of Be stars go unobserved in optical surveys because their disks are not permanent and have very variable structure. (Mc Swain 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. The Hα band is better suited to measuring variations in the disks of Be stars of all spectral types. Mc Swain et al. (2008) discovered a new Be star (130) in NGC 3766 whose Hα line not only changed in intensity, but the emission lines became absorption lines over a 4 years period, indicating that the star had an absorption disk that disappeared within one year. We will also explore the large variability detected in a fraction of Be stars, which is still not well understood. In a study on Be variability in an open cluster, Mc Swain et al. (2009) found no significant physical difference between variable and non-variable Be stars. Understanding variability patterns in Be stars populations opens the way for better modeling of angular momentum transport and its impact on mass loss for a key stellar mass range.

β **Cepheids** are massive O and B stars with sinusoidal light variations with periods ranging from 0.1 to 0.7 days, with amplitudes from 0.1 to 0.3 mag. A sub-type displays even smaller amplitude. Spectral types are B0 to B3, which makes them important for our study of the structures of B stars. The pulsations correspond to a stage at the end of core H burning, caused by bound-bound transitions of iron group elements, and extremely dependent on the metallicity. Mapping the Beta Ceph instability strip is an important goal to understand the final phases of evolution of massive stars. This has been attempted only for the Magellanic Clouds (Sterken & Jerzykiewics, 1988, Pigulski & Kolaczkowski, 2002), because long periods of observations are needed, and sometimes even spectroscopic follow-up to weed out objects that mimic the beta Ceph behaviour.

"V838 Mon" type of objects: Beautiful HST images illustrate the optical echo of V838 Mon (see Fig. 8), 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 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

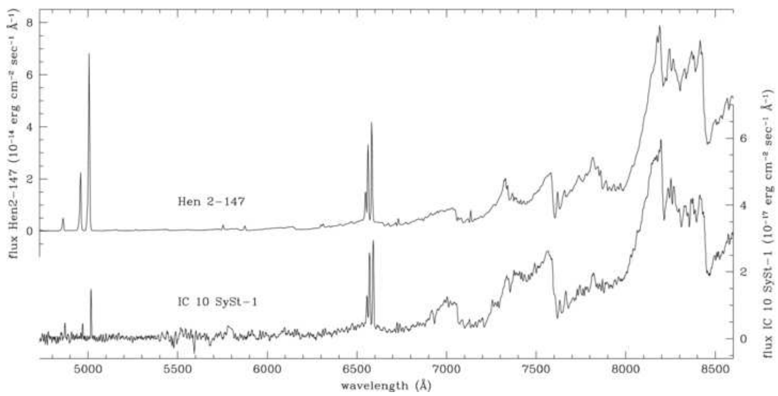


Figure 7: The optical spectrum of the symbiotic star StSy-1 in IC 10, a dwarf irregular and starburst satellite of M31, taken with two gratings and the CMOS-N detector at Gemini North, and comparison with the observed spectrum of the Galactic symbiotic Hen 2-147. See Goncalves et al. 2008 for details.

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 A large data base that will also be precious for...

Microlensing studies. Since the original proposal of Paczynski (1986), microlensing is an established tool of research 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.

Cepheids: There have been recent attempts to better determine the distance to M31 and M33 through the Cepheids (Vilardell et al. 2008), but the dependence of the Cepheids lightcurve on metallicity still needs improvement. This is of course a fundamental problem in astronomy, and one to which our data will contribute essential information.

Eclipsing binaries: We will obtain excellent light curves of 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 intercomparison of the derived distances without uncertainties for photometric calibrations.

The deepest Hα images of M31 and M33. Fig. 9 shows a beautiful image of one of the M31 fields imaged by Gallagher with WIYN and Mini-MO. Fig.2 illustrates the comparison with 4m NOAO telescope and the LGS. Although the *Living Galaxy* has many components that can be done with broad

Figure 8: 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?

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.

4 The cadence of monitoring: one program for many purposes

As Table 1 shows, planning the cadence of the observation presents some challenges because we do want to obtain useful data to study a variety of phenomena, including: a) long period variables like symbiotics, Miras, etc. with oscillations on time scales of years, b) variability of massive stars and microlensing events on timescales ranging to hours to many days, c) eruptive variables with large outbursts and flares that occur over many months but need to be followed at least weekly for classification purposes. Because the same objects however can have different time scales, and we may also discover whole new sets of phenomena over different time scales, we have decided that it is very important to have series of differently spaced exposures during the year.

The cadence scheme to achieve our scientific goals must also fit into the needs of telescope scheduling. The University of Wisconsin will have at most five consecutive nights when M31 and M33 are at low airmass. Around this time of the year the weather can also 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 only 2-3 consecutive whole nights, but we will also ask to be allowed to use 5-8 *half* nights during the period of

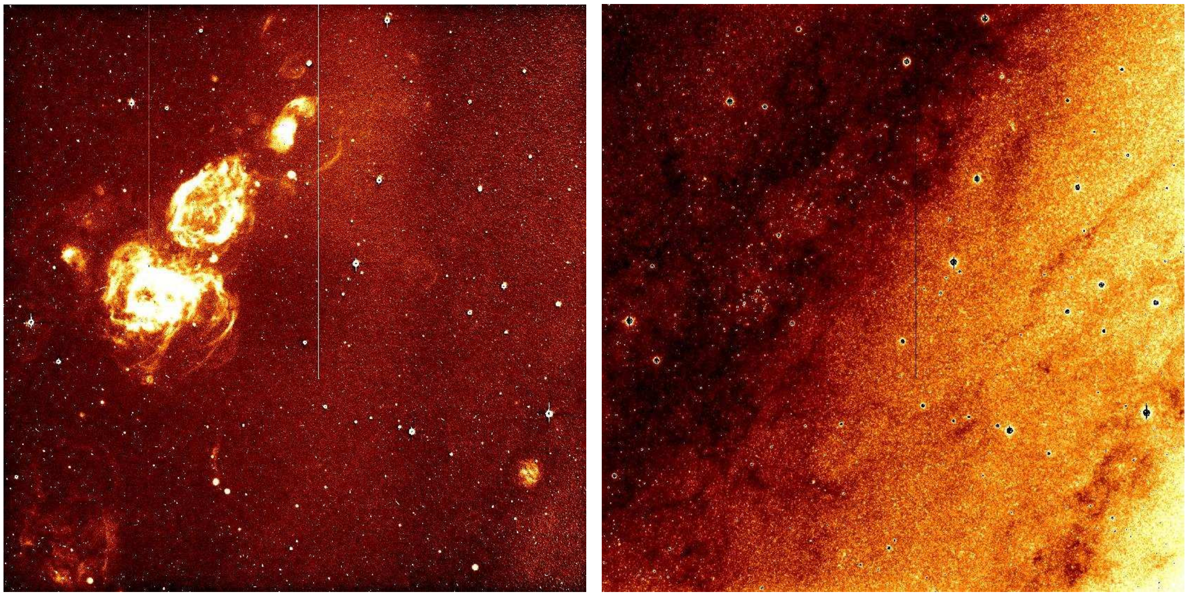


Figure 9: A field of M31 imaged in Hα by Gallagher with the WIYN Mini-Mosaic in a 15 minutes exposure. The Hα image after subtraction of the normalized R image is shown on the left, and the original R image is on the right. The R-image subtraction procedure allows faint structures to be resolved in detail.

longer visibility of the galaxies. We will ask that also the half nights are 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 order to plan the total exposure time we request, we have to take into account 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 dithered images. We will decide how often we plan to dither the images once some of the characteristics of the instrument are better known. At the moment the overhead time is not exactly known, but obviously with 8 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* even almost 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, probably renouncing 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 also possible improvements to the plan to obtain the cadence to maximize the science in case of missed observations due to weather and technical problems. The other big question concerns the mode in which the observations will be done. At this time there is no general users' queue set up yet for the use of ODI. During the Wisconsin nights, we will be able to share many nights with the other survey that is being planned and with other observers. However, we suggest that the UW would benefit from buying time from the queue of the Yale University for the Yale survey. Another possibility we are exploring 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 flters are necessary to distinuish source classes. If we go back to Fig.3, from the PTF, we find out that we need a weekly cadence to be able to detect novae, recurrent novae and other transients that are the most interesting to us:

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

tionTypes of variability of the major classes of variable systems and events we will observe, variability timescales and useful filters

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 Photometric references for M31 and M33

Both M31 and M33 have been fully photomered 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 Galaxy*, and we will be able to judge the quality of our photometry and improve it, when and if necessary.

There is one more important project that is relevant to us and this 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 resolutin template which will allow us to deconvolve WIYN images when variables are found in crowded regions.

The Hubble Panchromatic Survey includes ultraviolet filters. The ultraviolet images of this survey, when they become public, will be a powerful identification of the existence and precise position of variable sources in fields where even a circle with a radius of one arcsecond is too crowded to sort out the right optical counterpart of SSS and some other types of XRB, or even when the source is too faint for detection with other filters. Once we know the existence of a counterpart that we think will show orbital variability, even a method like pixel imaging with ODI will give the necessary information with optical filters.

6 A scientific niche for ODI: Comparison with other survey instruments

Although very wide field imagers are becoming more common, ODI at WIYN is a very competitive survey instrument in the Northern hemisphere. It is uniquely suited for a monitoring survey like the one we are proposing. Most wide field imagers are still of the class of 30x30 arcmin^2, so we will use 1/4th of the telescope to image the same field. If we have a close look at the "competition', in the Northern hemisphere, a comparable set of telescope+instrument is CFHT (Canada-France-Hawaii Telescope) with MegaCam. The best angular resolution is poorer than ours and only an instrument with a reduced FOV Hα filter (42x28 arcmin^2 FOV) is available.

Here we should mention that another type of monitoring survey, with a small-telescope and a very large field, is currently done by the team of the Palomar Transient Survey (PTF) with the 1.2m Palomar telescope and an 8 square degree imager, supported by the 1.5m telescope for some light curve measurement (Law et al. 2009). The PTF cannot resolve transients anywhere near the centers of galaxies, and does not use Hα filters, but we intend to collaborate with the PTF team to study some strategies to make our project more effective (see discussion in Section 4.2 and related and Fig. 5). Specifically to achieve the best plan for the cadence of our observations (Section 5).

The Subaru team is building Hyper-Suprime Cam, which will have an Hα filter, but an 8m telescope is dedicated mostly to distant object and cosmology and is not expected to be a monitoring survey instrument. Telescopes dedicated to surveys will be effective to study optical transients and variability in external galaxies, thus our competition will come primarily from Pan-Starrs, that also uses Orthogonal Transfer CCD's and eventually will be pointing with 4 telescopes at a 7 degrees^2 FOV. However, the Pan-Starrs collaboration does not plan to use an Hα filter, and at present the limiting magnitude of their survey (for given S/N and length of exposure) is 1.5 mag shallower than what we can and plan to achieve with WIYN, a really crucial limit for some of the populations we want to study at M31/M33 distance. Furthermore, it seems unlikely that Pan-Starrs can achieve image quality of $\leq$0.8 arcsec.

In the South LSST (the Large Synoptic Survey Telescope) will be much more effective than WIYN in terms of etendue (FOV x collecting area area) starting in 2016 or 2017. 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, making our project even more interesting.

7 Data management and analysis

After the first level of reduction, the one provided on site by the University of Indiana ODI data center, the first analysis of the *Living Galaxy* images will be set up by a post-doctoral collaborator we would like to hire, possibly in common with the ODISSE project. Co-I Calchi Novati will provide guidance, having large experience in the microlensing projects, especially with *pixel imaging software*. Another type of package we may want to use is the *Difference Image Analysis* (DIA) software. Both types of software allow to detect variability down to low levels even in non resolved images (e.g. the

5 inner arcminutes from the center of M31 and about 3 from the center of M33, regions that appear flooded with diffuse light in the WIYN exposures). In the respect of copy-rights of the microlensing software, we plan to train the post-doc to use this type of software and analyze all the images as they are obtained. This will allow us to detect and locate variablity as well as measure accurate photometry in “stamp like” sub images around the variables. Only in the most crowded core areas of few arcminutes accurate photometry will not be done, but there will be some spatial resolution and some measurements in our Hα images.

Full photometric pipelines will be done later, to set up a *Living Galaxy* archive in the future. We have also contacted a colleague at Padova who has worked with the Terapix collaboration, and are already exploring optimal ways this can be done. The Terapix group provides imaging and pipeline processing software to the CFHT MegaCAM and their (available) WiFIX software is of course of interest also for ODI.

8 The spectroscopic follow-up

Spectroscopic identification and follow-up will be an important part of the *Living Galaxy*, especially for transients and for the identification of new symbiotics (see Fig. 9). 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 magnitude of novae in outburst in M31 is in the V=15-18 range, and TNG can follow them spectroscopically even repeatedly 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 Galaxy*. Our co-I’s from Padova, already engaged in spectroscopic survey of M31/M33 novae, are leading experts in the of spectroscopy of novae and also of symbiotics, key components of the *Living Galaxy*.

Spectral are critical for assessing the physical nature of the transients. For example, Di Mille et al. (2010a and b) 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.

9 Collaborators

In addition to co-PI Townsend, our coI’s 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 Galaxy* in the areas of their expertise.

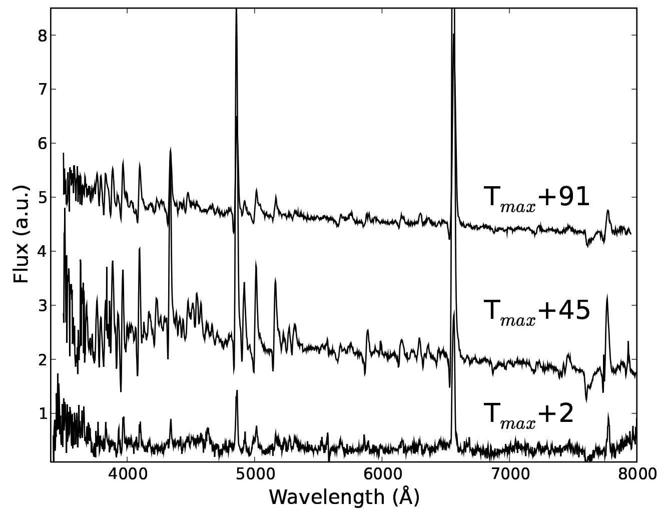
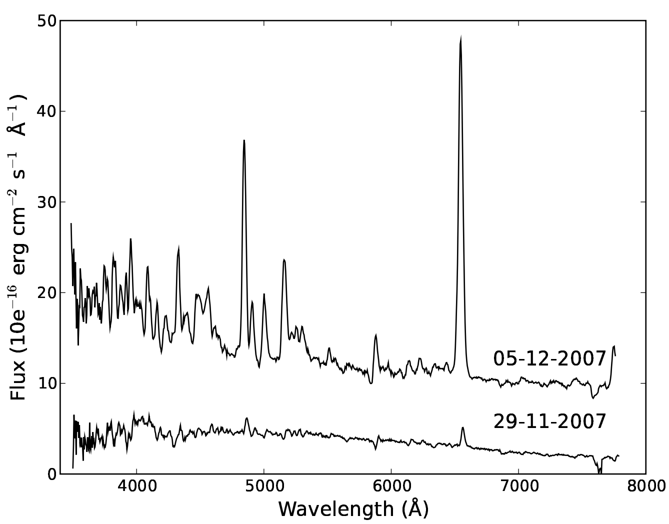


Figure 10: TNG spectra of nova NM31-2008-10b at different epochs

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 to

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



also 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 Time line

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 take into account exact overhead times, which may be as short as the 30 s 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 will 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.

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. Already 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* 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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