



**University  
of Victoria**

Graduate Studies

# **PROGRAMME**

The Final Oral Examination  
for the Degree of

**DOCTOR OF PHILOSOPHY**  
(Department of Physics and Astronomy)

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2009                      Whitman College                      BA  
Physics-Astronomy and Applied Mathematics

## **“Chemical Abundances of Local Group Globular Clusters”**

Thursday, July 31, 2014  
2:00 p.m.  
Clearihue Building, room A205

Supervisory Committee:

Dr. Kim Venn, Department of Physics and Astronomy, UVic (Supervisor)  
Dr. Don VandenBerg, Department of Physics and Astronomy, UVic  
(Member)  
Dr. Patrick Côté, Department of Physics and Astronomy, UVic (Member)  
Dr. Colin Bradley, Department of Mechanical Engineering, UVic  
(Outside Member)

External Examiner:

Dr. Catherine Pilachowski, Department of Astronomy, Indiana University

Chair of Oral Examination:

Dr. Cornelia Bohne, Department of Chemistry, UVic

## **Abstract**

Detailed chemical abundances of globular clusters in the Milky Way and M31 (the Andromeda Galaxy) are presented based on analyses of high resolution spectra. The unusual Milky Way cluster Palomar 1 (Pal 1) is studied through spectra of individual red giant branch stars; these abundances show that Pal 1 is not a classical globular cluster, and may have been accreted from a dwarf satellite of the Milky Way. The Milky Way globular clusters 47 Tuc, M3, M13, NGC 7006, and M15 are studied through their integrated light (i.e. a single spectrum is obtained for each cluster) in order to test high resolution integrated light analyses. The integrated abundances from these clusters reproduce the average abundances from individual stellar analyses for elements that do not vary within a cluster (e.g. Fe, Ca, and Ni). For elements that do vary within the clusters (e.g. Na and Mg) the integrated abundances fall within the observed ranges from individual stars. Certain abundance ratios are found to be extremely sensitive to uncertainties in the underlying stellar populations, such as input models, empirical relations to determine atmospheric parameters, interloping field stars, etc., while others (such as [Ca I/Fe I]) are largely insensitive to these effects. With these constraints on the accuracy and precision of high resolution integrated light analyses, detailed abundances are obtained for seven clusters in the outer halo of M31 that were recently discovered in the Pan-Andromeda Archaeological Survey (PAndAS) and are likely to have originated in dwarf galaxy satellites. Three clusters are relatively metal rich ( $[Fe/H] < -1.5$ ) for their locations in the outer halo; their chemical abundances suggest that they likely originated in one or more fairly massive dwarf satellites. The other four are more metal-poor, and may have originated in less massive dwarf satellites. These results indicate that the Milky Way and M31 have both experienced some amount of accretion from dwarf satellites, though M31 may have had a more active accretion history.

## **Awards, Scholarships, Fellowships**

- 2011-2014 Vanier Canada Graduate Scholar, *NSERC*  
2010 R.M. Petrie Memorial Award, *University of Victoria*  
2010 The M.A. & D.E. Breckenridge Graduate Award, *University of Victoria*  
2009 University of Victoria Fellowship, *University of Victoria*  
2007 Washington NASA Space Grant, *Whitman College*  
2005-2008 Walter Brattain Scholarship, *Whitman College*

## **Presentations**

1. Sakari, C.M.; McWilliam, A.; Venn, K.; Shetrone, M. D.; Dotter, A. L. and Mackey, D. "Abundances of Local Group Globular Clusters Using High Resolution Integrated Light Spectroscopy." American Astronomical Society (AAS) Winter Meeting #223, Washington, D.C., USA, January 2014. (oral)
2. Sakari, C.M., "High Resolution Integrated Light Spectroscopy of Globular Clusters." Landessternwarte, ZAH, Heidelberg, Germany, June, 2013. (oral)
3. Sakari, C.M., "High Resolution Integrated Light Spectroscopy of Globular Clusters." Argelander-Institut für Astronomie, Bonn, Germany, May, 2013. (oral)
4. Sakari, C.M.; Venn, K.A.; Shetrone, M.; McWilliam, A., and Dotter, A. "Integrated Light Spectroscopy of Galactic GCs at High Resolution." 10th Potsdam Thinkshop: High Resolution Optical Spectroscopy, Potsdam, Germany. May 2013. (poster)
5. Sakari, C.M.; Venn, K.A.; McWilliam, A.; Shetrone, M, and Dotter, A. "High Resolution Integrated Light Spectroscopy of Galactic Globular Clusters." The XII International Symposium on Nuclei in the Cosmos (NIC XII), Cairns, Australia. Aug. 2012. (poster)
6. Sakari, C.M.; Venn, K.A.; Irwin, M.; Aoki, W.; Arimoto, N. and Dotter, A. "Detailed Chemical Abundances of Four Stars in the Unusual Globular Cluster, Palomar 1." *3rd Subaru International Conference: Galactic Archaeology*, Shuzenji, Japan. Nov. 2011. (poster)

7. Sakari, C.M.; Venn, K.; Arimoto, N.; Aoki, W. and Irwin, M., "Detailed Chemical Abundances in the Unusual Globular Cluster Palomar 1." AAS Winter Meeting #217, Seattle, WA, USA. January 2011. (poster)
8. Sakari, C.M. and Miller-Jones, J. C. A. "The Proper Motion of Cygnus X-3." AAS Winter Meeting #213, Long Beach, CA, USA. Jan. 2009. (poster)

## **Publications**

1. Sakari, C.M.; Venn, K.; Shetrone, M.; Dotter, A.; Mackey, D. "Optimal Integrated Abundances for Chemical Tagging of Extragalactic Globular Clusters." *Monthly Notices of the Royal Astronomical Society*, **2014**, in press.
2. Sakari, C.M.; Shetrone, M.; Venn, K.; McWilliam, A.; Dotter, A. "Spectrum syntheses of high-resolution integrated light spectra of Galactic globular clusters." *Monthly Notices of the Royal Astronomical Society*, **2013**, 434, 358.
3. Mackey, A.D.; Huxor, A.P.; Martin, N.F.; Ferguson, A.M.N.; Dotter, A.; McConnachie, A.W.; Ibata, R.A.; Irwin, M.J.; Lewis, G.F.; Sakari, C.M.; Tanvir, N.R.; Venn, K.A. "A Peculiar Faint Satellite in the Remote Outer Halo of M31." *The Astrophysical Journal Letters*, **2013**, 770, 17.
4. Sakari, C.; Venn, K.; Irwin, M.; Aoki, W.; Arimoto, N.; Dotter, A. "Detailed chemical abundances of four stars in the unusual globular cluster, Palomar 1." *The Astrophysical Journal*, **2011**, 740, 106
5. Tudose, V.; Miller-Jones, J.; Fender, R.P.; Paragi, Z.; Sakari, C.; Szostek, A.; Garrett, M.A.; Dhawan, V.; Rushton, A.; Spencer, R.E.; van der Klis, M. "Probing the behaviour of the X-ray binary Cygnus X-3 with very long baseline radio interferometry." *Monthly Notices of the Royal Astronomical Society*, **2010**, 401, 890.