ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

OSSERVATORIO ASTROFISICO DI TORINO

INAF PhD Fellowship Proposal

Stars, Brown Dwarfs and Planets: Exploiting the Gaia L Dwarf Sample.

Proposed Host Institution *Università degli Studi di Torino* in collaboration with *INAF-OATo*

Thesis supervisor *Richard L. Smart* (INAF-OATo)

Co-supervisors *Beatrice Bucciarelli* (INAF-OATo)
Luciano Nicastro (INAF-IASF Bo)

The PhD student will carry out his/her research program at the Università degli Studi di Torino, where he/she will be supported by the following Institutions:

1. **Università degli Studi di Torino (UNITO).** A PhD program in "Physics and Astrophysics" is present at the Torino University. The Physics Departments have a number of collaborations with the INAF-Osservatorio Astrofisico di Torino, including a number of master theses based on Gaia data and three theses on the study of low-mass objects.

2. **INAF-Osservatorio Astrofisico di Torino (INAF-OATo)**. The Astrometry team of OATo has been working for many years in the production and analysis of ground and space-based wide field stellar surveys and studying nearby low-mass objects. The team is now heavily involved in the reduction of Gaia data, and will be able to provide precious insights of the Gaia data releases to the PhD student.

3. **Gaia Data Processing Center of Turin (DPCT).** Torino hosts the Gaia Data Processing Center (DPCT), one of the six data centers involved in the Gaia mission operations across Europe. This facility, which operates for the Italian participation led by M.G.Lattanzi (OATo) in the Gaia DPAC Consortium under an industrial contract awarded by ASI to ALTEC, will represent an ideal infrastructure for the manipulation and scientific analysis of the data available to the PhD student.

Proposed Research- Executive Summary

The proposed PhD research program will be to exploit the Gaia results to further our understanding of L dwarf objects. The research plan will follow the Gaia Data Release (GDR) schedule:

- Pre-GDR: Compilation of photometry and spectroscopy for known L dwarfs being observed by Gaia
- GDR1: Review Gaia L dwarf list; interpretation of color-color diagrams using Gaia + IR photometry, development of selection criteria, identification of all new L dwarfs observed by Gaia.
- GDR2: Review of distance-dependent calibrations; kinematic analysis and search for common proper motion objects. Scientific exploitation of the Gaia sample: derivation of the local luminosity function; characterization of benchmarks; correlations analysis of physical parameters such as age/mass vs. photometric/spectroscopic features.

Introduction

L dwarfs are objects that have masses encompassing the smallest stars, brown dwarfs and the largest planets; this sample will be dominated by brown dwarfs that are not able to fuse hydrogen and the lowest mass stars. The first L dwarfs were discovered only 20 years ago[1] but they were rapidly followed by 100s found in the large infrared sky surveys, and deep optical surveys[2]. These new objects led to the definition of the new L spectral types with temperatures ranging from 2500K to 1500K.

L dwarfs are very different from the majority of higher-mass stars in that they do not spend most of their lifetime with fixed physical parameters on a “main sequence”. This is graphically shown in Figure 1 where the three very different objects: a 7-Myr 9-Jupiter mass planet, a 90-Myr 30-Jupiter mass brown dwarf and an 8-Gyr 80-Jupiter mass low-mass star, are all spectral type L4-L5[3]. There is degeneracy between age and mass in this spectral range that is not present for higher-mass stars: unlike stars, these objects change significantly with age.

This degeneracy makes them very difficult to understand, but once we have correctly calibrated age -- or equivalently mass – indicators, it will prove to be one of their greatest strengths. A combination of lifetime-long evolution with age and ubiquity render them powerful chronometers to understand the evolution of the Galaxy and its substructures. These objects also provide test cases for the physics of large planets' atmospheres, and allow us to investigate the formation mechanisms of low-mass stars.

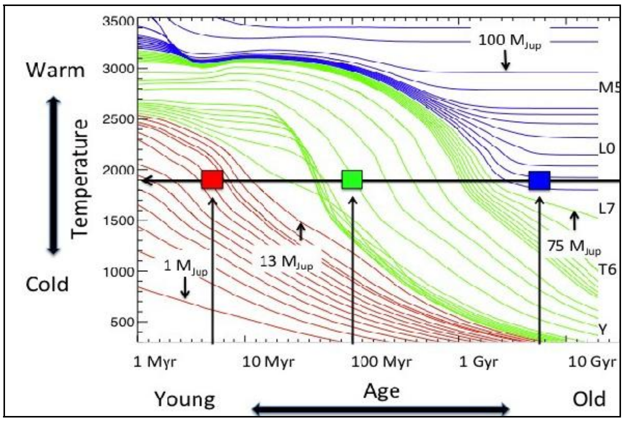

Figure 1: Models for the evolution of stars, brown dwarfs and planets.

The Contribution of Gaia

The ESA cornerstone mission Gaia launched on December 19th 2013 will revolutionize astronomy observing objects as diverse as minor planets, stars, galaxies out to QSOs and impacting almost all areas of astronomy. The limiting magnitude will be around 20 in the Gaia “G” band (close to Cousins R). Using the colors of known brown dwarfs and a Gaia-to-SDSS magnitude transformation, we have identified ~500 L0 to L5 dwarfs and a handful of L6 to T1 dwarfs[4] that are being observed by Gaia; they will result in parallaxes with accuracies of 0.1 to 0.3 mas, providing distances with relative errors of 1% -10% and tangential velocities with errors at the 10-30m/s level. We estimate our list of L dwarfs to be approximately 70% complete, with most of the new ones expected in the galactic plane where the ground-based surveys available today have crowding problems.

While the astrometry of the Gaia results will be a factor of 3-4 times better than current ground based sample, it’s main strength will be the size- 20 times the current ground based sample, completeness and homogenous nature – a complete magnitude-limited survey where the accuracy of the observational dataset and the ability

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[1] Nakajima et al. Nature 378:463, 1995., Ruiz et al. 1997, ApJL, 491, L107

[2] Skrutskie et al. 2006, AJ, 131:1163, Epchtein et al. 1997, The Messenger ESO, 87:27, York et al. 2000, AJ, 120:1579

[3] Adapted from Burrows 1997, ASPCS 119:9

[4] https://docs.google.com/spreadsheet/ccckey=0AhmmP_QTOg8kdHJjRk83bTNvaVJaMUhOdTIwR0lNZnc

to have parallaxes for all objects allows to control Malmquist, Eddington, and Lutz-Keller biases that plague all current statistical studies. The Gaia data, with already published low-resolution spectra, will fully map out the H-R diagram, revealing any companions down to less than a Jupiter mass. We will be able to compute bolometric magnitudes for this data set, and derive an estimate of their surface temperatures.
The full dataset will be searched for benchmarks, such as L dwarfs that are companions to main sequence stars or members of moving groups. Finally, Gaia's characterization of the Galactic population confronted with kinematic age determinations will place (loose) constraints on the ages of the L-dwarf subset.

The Contribution of New Spectra

A collaboration of Italian, Spanish, English and American institutes are building a medium-to-high resolution spectroscopic database of the Gaia L-dwarf sample. The knowledge of age and composition from benchmark objects and from Gaia-determined astrophysical characteristics of specific objects will enable an investigation of spectroscopic age and abundance indicators. The spectroscopic radial velocities will help the identification of moving group membership and to constrain and improve the Gaia astrometric solution.

Scientific Goals of the PhD

The potential scientific use of this dataset is very broad. The proponent has collaborated with the international partners on various hot topics: absolute magnitudes and temperatures[5], a very red binary system and a flux reversal L/T binary[6], the first T9 and T10 candidates and a red dusty L dwarf[7], constraining the local luminosity function[8]. A novel, precise, exquisitely homogeneous dataset will enable sound statistical investigations and drive the research in unpredictable directions. Here we briefly describe the anticipated impact of this project on our comprehension of the formation mechanisms for brown dwarfs, with the conscious expectation that the unexpected might be as, if not more, exciting.

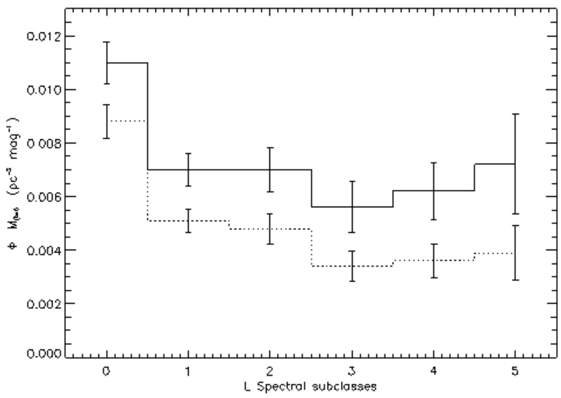

Figure 2 Source density predictions as a function of I spectral type. Predictions are shown for two different forms of the assumed mass function (α = 1.5 and 0.5, where dN/dM ≈ M^-α). The error bars are the Poissor noise for the Gaia sample in the respective bin.

A primary goal in astronomy has been to investigate the formation of stars and other objects from the dust and gas in the galaxy. Our understanding of stellar formation is quite well established, while the formation of smaller objects, – most notably brown dwarfs - remains an area of active debate. It is generally (though not unanimously[9]) believed that small amounts of gas, below the Jeans mass, cannot gravitationally collapse, and various other forces have been called into play to create smaller mass objects, e.g. turbulence[10], dynamical interactions[11], magnetic fields or hot star photo evaporation[12]. Probably all these forces are at play and their relative contribution may be environment-dependent and not unique. Observations of clusters and the field differ: is this indicating a change of dominant formation process? Has the formation process remained constant over the history of the galaxy? Is the dominant process a function of the metallicity of the basic material? Is there a low-mass cutoff to star formation? Many of these questions will find their answer in interpretations of the source density predictions. In figure 2 we present the source density predictions from simulations of the L -dwarf populations[13] along with error bars if we assume just Poisson noise for the Gaia samples. The two distributions which represent different formation scenarios are easily distinguished.

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5 Marocco, F., et al. 2013 AJ 146:161; Wang, Y. et al. 2014 PASP 126:15
6 Burningham, B., et al. 2010 MNRAS 404:1952; Gelino, C. R., et al. 2014 AJ 148:6
7 Smart, R. L. 2010 A&A 511:A30; Lucas P. W. et al. 2010 MNRAS. 408:56, Marocco, F. et al. 2014 MNRAS 439:372
8 Burningham, B., et al. 2013 MNRAS 433:457; Burningham, B., et al. 2010 MNRAS 406:1885
9 André, Ward-Thompson, & Greaves, 2012,Science, 337, 69
10 Boyd & Whitworth, 2005, A&A, 430, 1059. Padoan, et al., 2005, Mem. Soc. Astr. Italiana, 76, 187.
11 Reipurth & Clarke, 2001, AJ, 122, 432. Bate & Bonnell, 2005, MNRAS, 356, 1201.
12 Boss, 2004, MNRAS, 350, L57; Whitworth & Zinnecker, 2004, A&A, 427, 299.
13 Adapted from Burgasser 2004, ApJS, 155, 191.

National and International Context

This L-dwarf sample is already the focus of a large international collaboration to build a comprehensive database of their spectra and derived properties. This is being carried out by a number of institutions, in particular, directly in collaboration with INAF at the University of Hertfordshire, UK, and the Centro de Astrobiología, ES.

INAF has a number of researchers active in the study of brown dwarfs (Palla OAA, Stelzer OAP, Nicastro IASF and various researchers in OATo) and the exploitation of the Gaia results. In particular this research will aid in the development of the following national interests:

- The Gaia Astrometric Verification Unit - these are objects are at the extreme end of the Gaia magnitude range so testing in this area will characterize these results.
- Exploitation of large catalog databases from the PRIN CIWS, IPERCOOL, GSC2 and EUCLID preparation projects, in particular this is the contribution of Nicastro at IASF Bo.
- The production of supporting spectra via large ESO and International time observing proposals.

The University of Hertfordshire has an active low-mass objects group led by Prof. Hugh Jones and including Federico Marocco, David Pinfield, Nial Deacon, Ben Burningham amongst others. The group has already produced a number of studies that include spectra of the Gaia L-dwarf sample:

- 52 ORISIS/SOFI/Xshooter spectra of targets from the Parallaxes of Southern Extremely Red Cool (PARSEC) program [14] all of which are in the Gaia L-dwarf sample.
- 196 Xshooter spectra of L/T candidates[15] of which 80 are in the Gaia L-dwarf sample In addition Marocco and Smart have compiled around 300+ already published spectroscopic parameters as part of a GREAT long term visit during the end of 2014[16].
- The development in collaboration with Torino and Firenze observatories of the next generation instrument on the NTT, an infrared spectrograph with a precision at the level of Harps.

The Centro de Astrobiología and local collaborators: Drs Jose Caballero, Luis Sarro and David Barrado are active in all areas of ultra-cool-dwarf studies related to Gaia; in particular:

- Building the M-, L- and T-dwarf Archive of Interest for Astrophysics database (MAIA) a database of astrometry, multiband photometry, high- and low-resolution spectroscopy and homogeneously derived astrophysical parameters in preparation for the exploitation of Gaia. This dataset will be the primary repository that the PhD student will use.
- Leading an Osiris/GTC proposal for the spectroscopic observations of targets from the Gaia L-dwarf list in collaboration with the OATo group.
- Work package managers and members of Gaia GWP-S-835-30000 Ultra-Cool Dwarfs formally leading the data processing activity in this area.

In June 2015 the supervisor Smart will be in Madrid for 2 weeks to discuss the details of this part of the collaboration and other Gaia activities.

In addition there are a number of individuals interested and active on the collection of the supporting observations and the preparation for the exploitation of the Gaia L-dwarf sample that are collaborating with the OATo group, such as, but not limited to: J. Flaherty (Carnegie, US), R. Mendez (U.Chile, Chile), J. Beamin (U. Catolica, Chile), A Burgasser (U. San Diego, US), M. Cushing (U. Toledo, US).

[14] Marocco et al, 2013 AJ 146:1
[15] Day-Jones et al. 2013 MNRAS 430:1171
[16] see RLS-008 at http://www.cosmos.esa.int/web/gaia/public-dpac-documents

Availability of the necessary data to carry out the proposed research

The research program of the PhD student will be mainly based on the analysis and model comparison of the kinematics, distances, and astrophysical parameters for the thousand or so L dwarfs. These parameters will be derived by the astrometric and photometric measurements provided by the Gaia data releases cross-matched with the complementary photometric and spectroscopic catalogs currently available (see Table 1). The schedule for the Gaia data releases are detailed here: http://www.cosmos.esa.int/web/gaia/release. All these catalogs are, or will be, available to the PhD student through the archives maintained by the astrometric team of the Torino Observatory.

Assuming the student starts in late 2015 the program schedule will then be:

Work required	***Related timeline and Catalogs***	***Scientific Advances Permitted or Questions addressed***
Compilation of published photometry	4/2016, MAIA, Vista Surveys (released periodically, internal access granted), UKIDSS surveys (expected to end in 2015).	Refinement of candidate list, IR and red color-color diagrams.
Compilation of published spectroscopy	4/2016, MAIA, SPEX, ESO and other archives	Collation of spectral index values and estimates of radial velocities.
Add Gaia photometry and confirmation of candidate list.	6/2016 Gaia DR1	First optical color – color diagrams, refinement of transformations, indications of outliers in color space. First spectroscopic distance-based luminosity function
Add Gaia astrometry	1/2017 Gaia DR2	3D positions, 3D velocities, common proper motion pairs, correlations between ages and/or mass and spectral features.
Update Astrometry	1/2018 Gaia DR3	Indications of binary systems, slightly improved distances and other parameters.

Table 1. *Reference catalogs and timeline for the PhD research program.*

Note that the precision expected for the first release is at the 1-2mas level, which for these objects equates on average to a relative error of less than 5%. Subsequent releases will push the error down to sub-mass level and for many L dwarfs we will eventually have better than 1% accuracy; even so, a 5% error will be adequate to carry out most of the foreseen statistical analyses. As a comparison the current sample of L dwarfs with precise ground based parallaxes is around 50 at 1mas, the final Gaia list will be 20 times larger and 4 times more precise.

Curriculum Vitae Richard Laurence Smart

Education Record: PhD and Master in Astronomy at the University of Florida in 1993 and 1990. Bachelor of Science in Maths and Astronomy, II-I at Preston Polytechnic in 1986.

Employment History: Research Astronomer at the Osservatorio Astrofisico di Torino (INAF-OATo), Italy, since 2001. Royal Society Fellow and various Researcher level contracts at OATo from 1994 to 2001. Postdoc at the Space Telescope Science Institute 1993. Astronomy teaching and research assistant at the University of Florida 1988 to 1993.

Grant Received: PI EU FP7 IPERCOOL Staff Exchange Scheme 2010-2014; PI EU FP7 PARSEC incoming fellowship 2010-2012; PI INAF TNG Very Large Program grant 2011-2013; Coordinator Italy EU FP7 GENIUS Space Program 2013-2016, PI U. Barcelona, ES; OATo Coordinator PRIN INAF CIWS 2011-2013, PI IASF-Bo; Co-I Royal Society International Joint Project PI U. Hertfordshire, UK; Over 20 other travel, conference and research grants.

Institutional Responsibilities: Co-supervisor of the master's thesis of Federica Marocco 1998, Federico Marocco 2009, Mario Dapra' 2010 and Umberto Schirosi 2011; Supervisor of OATo postdocs/fellows: Fabrizia Guglielimetti 1997-98, Alexandre Andrei 2010-12, Catia Cardoso 2012-2013; Concorso committee member; EU grant evaluator; journal referee; Scientist responsible for the local 1.05m telescope; outside PhD evaluator.

Research Interests: brown dwarfs, low mass stars, astrometric techniques, data mining, galactic kinematics, construction of large catalogs.

Research Responsibilities: PI NPARSEC and PARSEC ESO large programs, PI TNG large program, PI Torino Parallax Program, PI UKIDSS parallax follow-up program. CoI on various HST, Spitzer and large telescope programs. Gaia: responsible for the Attitude Star Catalogue and the Initial Gaia Source List; co-manager for the Gaia Ground-Based Optical Tracking team; CU3 representative for the Ground-Based Observations for Gaia working group; collaborator on the Astrometric Verification Unit, the QSO input catalog, the GAREQ experiment, Coordinator for Italy in the FP7 GENIUS proposal for the dissemination of Gaia data. GSC2.3: responsible for the proper motion recalibration and the multimedia outreach product "The Making of GSC"

Publications: Author on over 60 (12 as first author) refereed publications, 35 (4) in the last 5 years and numerous proceedings, technical reports and outreach articles. Selected related references:

- **R. L. Smart & L. Nicastro 2014 AA 570:87 "The initial Gaia source list"**
- **F. Marocco et al. 2014 MNRAS 439:372 "The extremely red L dwarf ULAS J222711-004547 - dominated by dust."**
- **Y. Wang et al. 2014 PASP 126:15 "Parallaxes of Five L Dwarfs with a Robotic Telescope."**
- **C. R. Gelino et al. 2014 AJ 6:148 "WISEP J061135.13-041024.0 AB: A J-band Flux Reversal Binary at the L/T Transition."**
- **R. L. Smart et al. 2013 MNRAS 433:2054 "NPARSEC: NTT Parallaxes of Southern Extremely Cool objects. Goals, targets, procedures and first results."**
- **F. Marocco et al. 2010 AA 38:524 "Parallaxes and physical properties of 11 mid-to-late T dwarfs."**
- **B. Burningham et al. 2013 MNRAS 433:457 "76 T dwarfs from the UKIDSS LAS: benchmarks, kinematics and an updated space density."**
- **A. H. Andrei et al. 2011 AJ 54:141 "Parallaxes of Southern Extremely Cool Objects. I. Targets, Proper Motions, and First Results."**

PhD Student Training Plan

The PhD student will attend the fundamental courses required by the rules of the PhD program in *"Physics and Astrophysics"* of the University of Turin. The observatory is active in the UniTo program with the Astrometry group providing two courses to the department Master and PhD program.

At the INAF-OATo, he/she will be supported by a team of astronomers who are working on Gaia and the study of low mass stars, brown dwarfs and planets. This team includes:

- *Beatrice Bucciarelli* (senior research astronomer). Scientific interests: techniques for high-precision astrometry, photometric catalogs, statistical analysis of data. She teaches "Methods of Astrometry for Astrophysics" to students of the "laurea specialistica "in Physics at UNITo.
- *Mario G. Lattanzi* (associate astronomer). Scientific interests: high-precision astrometry from ground and space; all-sky stellar catalogs; stellar populations; galactic studies. In collaboration with Dr Bucciarelli he is teaching "Methods of Astrometry for Astrophysics" at UNITo. He is the P.I. of the Italian participation in the astrometric mission Gaia.
- *Richard L. Smart* (senior tecnologo). Scientific interests: brown dwarfs; Galactic kinematics and evolution; precision astrometry reduction and analysis procedures; construction and access of large catalogs.

In addition, the PhD student will be encouraged to attend national and international Schools, workshops, and conferences than can improve his/her expertise in the field of the low-mass stars, brown dwarfs and planets as well as to familiarize with the *data model* of the Gaia catalogue.

The student will spend an extended period working with collaborators at the University of Hertfordshire to develop experience in the interpretation of spectra and at the Centro de Astrobiología for the use of the MAIA database.

He/she will be also involved in the training activities promoted by the GREAT[17] Research Network Programme, which is a pan European science driven research infrastructure supported by the EC through the European Science Foundation (ESF) and the Initial Training Network (ITN) programme. The aim of GREAT is to facilitate the fullest exploitation of the Gaia catalogue.

He/she will collaborate on the data dissemination program of Gaia with the coordination unit 9 and the EU FP7 Space Program: Gaia European Network for Improved User Services, GENIUS[18], for which the supervisor is the Italian Coordinator.

[17] http://www.ast.cam.ac.uk/ioa/GREAT/
[18] http://genius-euproject.eu/