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FONDO NACIONAL DE DESARROLLO CIENTIFICO Y TECNOLOGICO (FONDECYT)

Moneda 1375, Santiago de Chile - casilla 297-V, Santiago 21
Telefono: 2435 4350 FAX 2365 4435
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INFORME FINAL
PROYECTO FONDECYT POSTDOCTORADO

OBJETIVOS
Cumplimiento de los Objetivos planteados en la etapa final, o pendientes de cumplir. Recuerde que en esta sección debe referirse a objetivos desarrollados, NO listar actividades desarrolladas.

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<th>OBJETIVOS</th>
<th>CUMPLIMIENTO</th>
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<td>1</td>
<td>Finish up the analysis of the 2 year data, as well as prepare and submit our final year 3 proposals.</td>
<td>TOTAL</td>
<td>This was the first goal written in the proposal. It has been fully completed. By the time of writing this report, all the data have been analysed and we also submitted the proposal. In the last semester (2016B) we only submitted one proposal to Gemini under the Fast Turnaround mode. It was accepted but due to the poor weather conditions, the proposal was not observed. We also sent a proposal to Gemini North and South together with some collaborators in the US. It was accepted and the observations are being carrying out at this time.</td>
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<td>Write letter/papers based on the final datasets obtained as well as finish up any loose ends toward the publication of the year 2 papers.</td>
<td>TOTAL</td>
<td>I have 3 papers in different stages of writing. One has been affected by the poor weather conditions in the observatories that prevented us to completely characterise a black hole candidate. The second paper is based on the detection of sources in the Norma Arm with the NuSTAR X-ray satellite. This draft is almost written and I intend to submit it before the end of the year. The third paper is based on the optical and near-infrared analysis of a black hole candidate. This draft is finished and waiting for input of some co-authors.</td>
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<td>By the end of the year we expect to have published at least 3 papers during the length of the position or at least be in the final stages of publication for all of them.</td>
<td>TOTAL</td>
<td>This was the third goal mentioned in the proposal of the project. At this moment we have already published 6 papers during the length of the position and there are at least 5 more in different stages of writing. 2-3 of them will be submitted before the end of 2016.</td>
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Otro(s) aspecto(s) que Ud. considere importante(s) en la evaluación del cumplimiento de objetivos planteados en la propuesta original o en las modificaciones autorizadas por los Consejos.
RESULTS OBTAINED:
The main goal of this project was to increase the census of stellar-mass black holes in our Galaxy. To do so, we proposed to perform an observational effort in optical and near-infrared wavelengths in order to confirm the nature of already known black hole candidates, and also to perform NIR follow-up of targets selected by the Chandra and NuSTAR surveys. Since there are only \( \sim 20 \) black holes already confirmed in the Galaxy in the last 50 years, this project was ambitious in its goals. However, we have successfully achieved our aims with the detection and indirect confirmation of another black hole candidate, the confirmation of the most massive black hole in our Galaxy and the publication of the most updated and thorough catalog of these systems. In addition, we have also achieved our secondary goals, i.e., the study of new or old objects that have gone into outburst during the duration of the project. Below, we detail the progress made in this project:

1. **BlackCAT: The catalog of black holes**
   For more than a year, we were working in the most updated and thorough catalog of Galactic black holes. To do so, we had to compile all the information published about the 60 black hole candidates already discovered since 1966. It was a major work since it implied the lecture of more than 400 publications of all kind which implied the compilation of more than 5000 items to complete the catalog. Thanks to this work, we were able to estimate that the black hole population in the Galaxy should be of 1300 objects, being the first estimate based on the observational parameters. This catalog will be permanently hosted in the servers of the Pontificia Universidad Católica de Chile and it was also published in Astronomy & Astrophysics journal: Corral-Santana, J. M.; Casares, J.; Muñoz-Darias, T.; Bauer, F. E.; Martínez-Pais, I. G. & Russell, D. M.: *BlackCAT: A catalogue of stellar-mass black holes in X-ray transients*, 2016, *A&A* **587**, A61.

2. **Swift J1357.2-0933: The most massive stellar-mass black hole in the Galaxy**
   Swift J1357.2-0933 was discovered in 2011 during an X-ray outburst. With the data taken during that phase, we could obtain the orbital period of the binary system (2.8 h; the second shortest among the black hole transients). We also detected an obscuring structure moving along the accretion disc which caused profound dips in the light curve and implying an edge-on inclination (i.e. 90\(^{\circ}\)). Recently, with spectroscopy taken in the 10.4 m GTC telescope when the system reached its quiescent state, we were able to obtain the radial velocity of the secondary star \( (K_2 \sim 1000 \text{ km/s}) \). This, combined with our
previous estimate of the orbital period implies a mass of the compact object of at least 8.3 $M_\odot$, which become Swift J1357.2-0933 in the most massive black hole in the Galaxy. In addition, these spectra allowed us to confirm both the orbital period and the inclination of the system, being also the first black hole transient found in an edge-on configuration.


3. **Discovery and indirect confirmation of a black hole in KY TrA**

KY TrA was detected in 1974 by the Ariel V instrument during an X-ray outburst. The optical counterpart was identified 12 days after the peak of the outburst, however, no further optical studies have been done since. Actually, the optical counterpart was lost when the system went into the quiescent state due to its faintness. Thanks to a large observational effort obtaining both photometry and spectroscopy, we could detect the true optical counterpart performing a $(r' - H\alpha)$ vs. $(r' - i')$ diagram where all H\alpha emitters (such as black hole transients) clearly segregates from normal field stars. In addition, we performed an astrometrical analysis to disentangle the true counterpart from a nearby star. Finally, with indirect measures of the orbital period and the radial velocity, we could estimate a BH with at least 9 $M_\odot$.

These results were published in Zurita, C.; Corral-Santana, J. M. & Casares, J.: *The Historical X-ray Transient KY TrA in quiescence*, 2015, MNRAS 454, 3351-3356

4. **New outburst and follow-up analysis of the black hole BW Cir**

BW Cir is a already confirmed black hole which was originally detected in 1987. Since then, it has had 2 more outbursts: 1997 and 2015. Studies of these systems in outburst are extremely important since it is the only moment in which we can perform analysis of the accretion flow. Once the system reaches the quiescent level, the companion star dominates the optical flux and therefore we can perform dynamical studies but it prevent us to obtain information of the accretion disc. Thus, we took advantage of the observational facilities grounded in Chile to observe the system in outburst and follow-up BW Cir in during the whole phase until it reached the quiescent state. In addition, we joined efforts with our collaborators to also analyse the long-term evolution of the system during 7 years, detecting a slow rise in the flux that might have cause an increase in the accretion rate and eventually triggered the new out-

2
5. Collaboration on Galactic archaeology
During my time at the Pontificia Universidad Católica de Chile, I could also establish new collaborations with other researchers working in different areas. Thus, I have also participated in projects related with neutron stars and globular clusters. Therefore, I have participated in a paper searching for tidal debris of dwarf galaxies around globular clusters, where we presented a comprehensive wide-field photometry database collected from both hemispheres (INT and ESO2.2m telescopes).

6. Kinematics of the Sagittarius tidal stream
In addition, given my large expertise with the reduction and analysis of spectra, I have also participated in a project analysing radial velocities of stars around the globular cluster Whiting 1 that belong to the Sagittarius tidal stream. We find 2 different components in the radial velocity distribution, confirming the association of Whiting 1 with the tidal stream but also the first direct observation of the old leading arm of that halo substructure.
This result will be submitted to MNRAS a few days after the end of the FONDECYT project since it is in its final stage of preparation: Carballo-Bello, JA; Corral-Santana, JM; et al.: The leading and trailing wraps of the Sagittarius tidal stream around the globular cluster Whiting 1, 2017, MNRAS, almost submitted

Prospectives and future work/publications
In addition, there are other publications ongoing that will appear after the official end of the FONDECYT project but the bulk of the observations, reduction, analysis
and/or writing has been done during this project. Thus, all of these publications will have the corresponding acknowledgement to the project and they deserve to be considered as part of the FONDECYT project. Below, you can find the details of these publications:

- We have made a thorough analysis of the black hole candidate MAXI J1659-152 covering 5 years data. In this paper, we find the photometric orbital period of the system being 2.4h, the shortest orbital period found among the black hole transients. We also detect the optical counterpart in quiescence and argue against a possible interloper star proposed by other authors, confirming that the proposed counterpart is the true one. This paper is already finished and sent to the co-authors. It will be submitted very soon to MNRAS and we expect to have it published at the beginning of 2017.

- We have also finished the analysis of the whole sample of near-infrared follow-up spectra obtained within the NuSTAR Observatory’s Galactic Survey. The ∼30 spectra were taken with MMIRS at the 6.5 m Magellan telescope with the aim to confirm the nature of several dozen of high-mass X-ray binary candidates previously detected with the Chandra and NuSTAR satellites. We are now in the latest stages of finishing the writing of the draft on the most important sources. Besides, together with our collaborators, we expect to publish the main paper of the collaboration before the end of 2016. Thus, at least 2 publications will be published about this topic.

- We also followed-up the outburst of the black hole GX 339-4 which happened in 2015. Analogously to what happened with BW Cir, we want to publish the analysis of the outburst and subsequent decay of this system. We are starting to write this paper.

- The first orbital modulation of the black hole candidate NOph93. This system was detected in 1993 and nothing has been done since. Our light curve is the first one obtained on this system and suggest an orbital period of >8 hours. Using an empirical relation between the amplitude of the outburst (∆V ∼ 7) and the orbital period, we estimated an upper limit of 9.2 hours on the orbital period. Unfortunately, given the bad conditions of the nights we observed, we could partially cover the orbital period, avoiding us from obtaining it. Thus, we have recently submitted (proposals in evaluation) two complementary proposals to obtain the orbital period, the most fundamental parameter of an X-ray transient, and the radial velocity of the companion star. Both values will give us the mass function of the binary system and therefore the dynamical
confirmation of a black hole in NOph93. Note that this would be the first confirmation of a black hole in 4 years and the second in the last 13 years. We were granted with observing time to confirm the orbital period of this neglected black hole candidate. However, during the nights assigned to this project in 2016A, the weather was extremely bad with snow and strong wind and, therefore, we could not complete this project. We have asked for more observing time in 2017A to finish this goal on the next semester and publish the paper.

- In addition, we have submitted a proposal to discover the first black hole transient ever detected. It was detected in 1966 with a X-ray rocket when the system was in outbursts, but due to the extremely bad accuracy in the pointing, it was not possible to find a counterpart. Since then, the system has remained in quiescence. Now, we propose to use the huge field-of-view of DECam mounted on the 4-m Blanco Telescope in Cerro Tololo to cover a wide area around the position of this source several times during a night. This will give us all the sources with variable light curves and combining with the Hα emission using the VPHAS+ survey, we will be able to discover the optical counterpart. Given the bad sensitivity of the X-ray detectors at that time, we believe that the system must be one of the brightest X-ray transients ever detected.

Finally, during the last year I has applied for several positions to continue with my research career. Thus, I was granted with a postdoctoral fellowship position to work in the European Southern Observatory in Chile.
ACHIEVEMENTS OF THE PROJECT:
During my 3 year FONDECYT postdoc, I have attended several national and international conferences, leaded observational campaigns and published several papers in international journals. In addition, there will be at least 5 more papers to be published in the next months which could not be published within these 3 years, however, the bulk of the work have been done during the FONDECYT project. Therefore, all these papers will do have the corresponding acknowledge to the FONDECYT project. Below, there is a detailed list of the main achievements obtained along this project.

List of publications during the FONDECYT project
- Optical photometry of the black hole transient GS 1354-64 (BW Cir) in outburst, Corral-Santana, Muñoz-Darias, Carballo-Bello, & Bauer; 2015, ATel#7620, 1

Publications in preparation mainly done during the FONDECYT project
- Observations of the black hole candidate MAXI J1659-152 during the 2010 outburst and quiescence, Corral-Santana, Shabbaz, Russell et al. Draft sent to collaborators. To be published at the beginning of 2017.
- The NuSTAR hard X-ray survey of the Norma Arm region, Fornasini et al., incl. Corral-Santana and Bauer. To be submitted soon.
- The leading and trailing wraps of the Sagittarius tidal stream around the globular cluster Whiting 1, Carballo-Bello, Corral-Santana et al. To be submitted to MNRAS in November 2016.
- On the orbital period of the neglected black hole candidate N. Oph 93, Corral-Santana et al. Pending of additional observations to be obtained in 2017A.

Attended conferences:
- The Unquiet Universe: The local Universe, oral contribution.
- European Week of Astronomy (EWASS 2015), poster.
- 5th VVV Sience Meeting, oral contribution.
- 6th VVV Sience Meeting, poster.
- XII Reunión Anual de la Sociedad Chilena de Astronomía, poster.
- XV Latin American Regional IAU Meeting, oral contribution.

Research visits:
- Instituto de Astrofísica de Canarias (IAC; Spain)
- University of Oxford (United Kingdom)
- Netherland Institute for Space Research (SRON; Netherland)
- New York University Abu Dhabi (NYUAB; United Arab Emirates)
- Texas Tech University (Texas, USA)

Telescope time granted
During the 3 years of the FONDECYT, we obtained 4 observing nights at the Magellan Telescopes, 4 nights at SOAR, 3 nights at DuPont and 45 h with the SMARTS 1.3 telescope and Las Cumbres Google Observatory. Unfortunately, the weather conditions during the vast majority of these nights were extremely poor, which have had direct impact in the results of this project.
During the course of this FONDECYT postdoctoral fellowship, Jesús Corral-Santana has made a strong impact on field and (in the face of some observational adversity, both from the weather and the time allocation committees) has exceeded the expectations he laid out for himself in his original proposal. In terms of research, Jesús has been quite productive and has maximized his existing resources. During his 3 yr fellowship:

Jesus published a large statistical compilation all known black hole candidates (dubbed “BLACK CAT”; Corral-Santana et al. 2016), as well as designed and implemented a web-based information repository for visualization of the catalog. By putting all of the information in one place, in a uniform format and with regular updates, this catalog provides the community with a unique and powerful resource for understanding the formation and emission from stellar mass black holes. Based on the citation rate over the past ~1 yr, the catalog has been well-received and is a valuable reference.

Contemporary with this effort, Jesús has been able to place new constraints on a number of candidate stellar mass black hole binaries in order to increase the population of confirmations to statistically interesting levels (KY TrA, Swift J1357.2-0933, BW Cir, MAXI J1659-152, N. Oph 93, and GX 339-4). This has led to a few publications, with several more in progress.

Finally, Jesús participated in my collaboration with the NuSTAR Observatory’s Galactic Survey team. In particular, Jesús and I have been carrying out NIR follow-up observations of several dozen high-mass X-ray binary candidates (HMXBs) culled from the Chandra and NuSTAR imaging surveys of the Norma star forming region. Jesús took the lead on the reduction and analysis of spectra for 20-30 candidates, which we intend to publish with our international collaborators by the end of 2016.

Overall, Jesús’ work have had broad implications for understanding the formation and evolution of stellar mass black holes, both individually (to understand their physics) and collectively (to understand their possible formation channels and demography). He has strategically attended several conferences in Europe and the US, where he has presented his work to favorable accolades and made several valuable connections and collaborations with key researchers in the field. In this sense, Jesús is operating well in an independent and self-sustaining manner.

In addition to Jesús' productive research, he has been a model citizen at IA-PUC, regularly attending science talks, participating in daily discussions, and providing diverse opinions that can spark ideas and creativity in others during my eclectic research group meetings. He has initiated a several collaborations both in Chile and abroad, which have pushed his development. His presence has helped to foster a strong and diverse academic environment at IA-PUC, which is critically important for the continuing growth and development of both our institute and our students. The success obtained during this FONDECYT fellowship has allowed Jesús to win an ESO Fellowship, which he is taking in Chile, and thus we aim to maintain collaborative ties.

Sponsor signature

Date: 29/10/2016
PRODUCTOS

ARTÍCULOS
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| Indexación                | ISI |
| ISSN                      | 1365-296 |
| Año                       | 2015 |
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| Páginas                   | 2199-2204 |
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The Historical X-ray Transient KY TrA

Optical photometry of the black hole transient GS 1354-64 (BW Cir) in outburst

A search for stellar tidal debris of defunct dwarf galaxies around globular clusters in the...
The leading and trailing wraps of the Sagittarius tidal stream around the globular cluster Whiting 1
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Nº : 6
Autor (a)(es/as) : Corral-Santana, JM.
Título (Idioma original) : Hunting stellar-mass black holes in X-ray binaries
Nombre del Congreso : XV Latin American IAU Meeting
País : COLOMBIA
Ciudad : Cartagena
Fecha Inicio : 02/10/2016
Fecha Término : 08/10/2016
Nombre Publicación : Proceedings XV Latin American IAU Meeting
Año : 2017
Vol. :
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Envía documento en papel : no
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Corral-Santana_JM_abstract_Talk_v2.pdf

Nº : 7
Autor (a)(es/as) : Carballo-Bello, JA; Corral-Santana, JM; Sollim, A; Muñoz, R.R.; Martínez-Delgado, D.
Título (Idioma original) : Whiting 1: Confirmation of its acretion by the Milky Way
Nombre del Congreso : XV Latin American IAU Meeting
País : COLOMBIA
Ciudad : Cartagena
Fecha Inicio : 02/10/2016
Fecha Término : 08/10/2016
Nombre Publicación : Proceedings XV Latin American IAU Meeting
Año : 2017
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Título (Idioma original) : A "high-hard" outburst of the black hole X-ray binary GS 1354-64
Nombre del Congreso : American Astronomical Society, AAS Meeting #228, id.402.06
País : ESTADOS UNIDOS DE AMERICA
Ciudad : San Diego
Fecha Inicio : 12/06/2016
Fecha Término : 16/06/2016
Nombre Publicación :
Año : 2016
Vol. :
Nº :
Páginas :
Envía documento en papel : no
Archivo Asociado :
Koljonen2016_AASmeeting.pdf

Corral-Santana, JM.

Título (Idioma original) : Searching for X-ray binaries within the VVV survey
Nombre del Congreso : 5th VVV Science Meeting
País : CHILE
Ciudad : Concón
Fecha Inicio : 03/04/2014
Fecha Término : 05/04/2014
Nombre Publicación :
Año :
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Páginas :
Envía documento en papel : no
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ANEXOS

A continuación se detallan los anexos físicos/papel que no se incluyen en el informe en formato PDF.