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CN2023A-25

Galactic panel
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(Resuming) A Clean Test of Gravity at Very Weak Accelerations

Abstract

We propose to resume a CNTAC program designed to provide the first unambiguous test for the behavior of gravity in the uncharted regime of accelerations that leads to the necessary adoption, under standard cosmology, of large quantities of dark matter surrounding galaxies. This is the only available test today that is free from the ambiguities associated to the potential presence of any dark matter. Our gravity test consists in measuring the 3D orbital velocities of very wide binary systems specifically chosen as having the highest quality astrometry delivered by Gaia. Our program therefore consists of the measurement of the remaining velocity dimension, i.e., the radial velocities, of the components of the target binaries to precisions comparable to those of extrasolar planet studies. As suggested by the CNTAC, we first conducted a 1-yr pilot study that demonstrated the soundness of our strategy. But then the pandemic hit. Here we request Long Term status to pursue the full program.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
FEROS/MPG 2.2-m	6 nights	4 nights	Any Any	Any Any

CoIs

Name	Institution	e-mail	Observer?
Rafael Brahm	UAI	rbrahm@gmail.com	True
Jeff Andrews	OnCL	jeffrey.andrews@ufl.edu	False
Marcel Agueros	OnCL	marcel@astro.columbia.edu	False
Scott Tremaine	OnCL	tremaine@ias.edu	False
Simon White	OnCL	swhite@mpa-garching.mpg.de	False
Sebastian Vilaza	PUC	svilaza@uc.cl	True
Pedro Figueira	OnCL	pedro.figueira@unige.ch	False

Status of the project

- Past nights: 7
- Future nights: 18
- Long term: True
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
Pair001A	07:11:50.55	-29:09:01.26	G=10.8577
Pair001B	07:11:46.80	-29:08:57.84	G=8.9182
Pair002A	05:45:56.00	-15:47:38.06	G=8.9039
Pair002B	05:46:00.73	-15:48:01.40	G=11.2836
Pair003A	10:53:20.15	-43:15:45.47	G=9.5038
Pair003B	10:53:20.28	-43:16:00.47	G=9.0486
Pair004A	07:46:14.84	-59:48:50.63	G=7.9312
Pair004B	07:46:16.96	-59:48:34.19	G=8.0514
Pair005A	01:55:49.82	-29:06:50.02	G=7.0674
Pair005B	01:57:11.54	-29:10:24.88	G=11.9931
Pair006A	01:43:14.18	-21:36:56.30	G=9.6808
Pair006B	01:43:14.32	-21:37:11.17	G=8.0158
Pair007A	21:06:54.17	-04:35:18.71	G=10.2136
Pair007B	21:06:54.48	-04:35:16.47	G=10.3306
Pair008A	13:30:16.33	-36:11:44.13	G=9.5140
Pair008B	13:30:19.26	-36:12:25.43	G=10.6589
Pair009A	13:02:07.16	+07:16:51.63	G=10.1105
Pair009B	13:02:07.86	+07:16:46.93	G=9.0125
Pair01A	14:16:47.58	-72:23:56.2	G=9.834166
Pair01B	14:18:17.87	-72:25:05	G=10.21355
Pair02A	04:02:10.02	-66:33:40.37	G=11.409089
Pair02B	04:02:25.32	-66:33:07.34	G=10.863148

SCIENTIFIC AIM AND RATIONALE

Dark matter is one of the main ingredients of our current cosmology, ΛCDM, yet this is the case despite the increasingly worrisome fact that it continues to elude all efforts for its direct and indirect detection. All present-day evidence for its existence is of astronomical nature, and a large part of this evidence comes from the application of Newtonian dynamics (as a limit of General Relativity in the appropriate limit) to stars and gas in orbit at kpc distances from the centers of galaxies, where their rotation curves are observed to flatten. **However, it is often not realized, or largely overlooked, that applying Newtonian dynamics to this specific problem is, formally, an extrapolation of the theory**. This in the sense that, until today, there are no actual experiments, in the lab or even involving astronomical observations, in which Newtonian dynamics has been tested and validated for the regime of accelerations ($\sim 10^{-10}$ ms^{-2} and smaller) experienced by the stars and gas that act as test particles in the determination of the total mass of galaxies. There are also no precision tests of Newtonian dynamics on any scales larger than our planetary system (with possible exceptions being globular clusters, though in dynamical cluster models there are plenty of free parameters; and comets, where the consistency of models of the Oort cloud tests gravity up to a few tenths of a parsec). **This constitutes one of the main motivations behind the appearance of alternative theories of gravity, such as MOdified Newtonian Dynamics (MOND), and many others.**

Clearly, any practical ideas for clean, unambiguous experiments that can probe and constrain gravity at such weak levels of acceleration are of large importance today. **Note, therefore, that this is not a proposal for a program on alternative theories, but rather a proposal for a test of fundamental gravity in a regime where the standard theory has not been tested yet.** Our program is thus motivated by the fact that the orbital accelerations felt by the components of very wide binaries, with semimajor axes of a few thousand AUs and larger, fall within this special regime of gravity. **In addition, they do so without the ambiguities associated to the potential presence of any dark matter, thus offering us this important and rare opportunity.**

In principle, the test with wide binaries is straightforward. Newtonian gravity predicts that binaries with increasingly larger separations have decreasing orbital velocities (i.e., Keplerian dynamics), whereas modified gravity models predict a flattening of the orbital velocity at large separations. Although the orbital periods for these binaries are orders of magnitude longer than a human lifespan, in principle the orbital velocities of even these extremely long periods can be measured as the difference in the 3D spatial velocities of the wide binary components. **However, not only these measurements probe the state-of-the-art in astronomical instrumentation, but the interpretation of the best data available are plagued by a series of systematic effects and biases.**

Because of their failure to account for these systematic effects (described below), all but one of the known attempts to perform this test using wide binaries have all concluded, wrongly, that these systems show clear departures from the expectations of Newtonian dynamics which would require us to abandon it in favor of MOND or similar alternatives (Hernández et al. 2012; 2018; 2021; Scarpa et al. 2017). It is likely because of this failure that none of these works have been published in astronomy mainstream journals. The one exception is the work by Pittordis & Sutherland (2019,2022), where they conclude, rightly, that Gaia data are inconclusive for this test today using astrometry alone. **In this proposal, we demonstrate that the test can be done correctly over a few years, accounting for all known systematic biases, using current state-of-the-art instrumentation available from the CNTAC, and propose a plan to carry it out from Chile.**

THIS PROPOSAL: We propose a program aimed to provide the first, unambiguous test for the behavior of gravity in the regime of accelerations relevant for the problem of dark matter in galaxies. For this, we have selected the best available sample of very wide binaries, which today is allowed by the exquisite astrometry from the Gaia mission, currently on its Data Release 3.

For the test to provide reliable conclusions, **the demand in velocity precision** is set by the vertical distance between the blue and red regions in Figure 1, which show the theoretical expectations for the orbital velocities of wide binaries under Newtonian and MOND dynamics (simple MOND, with no external field effect), respectively. For a 1 $M_\odot$ binary, this difference in expected orbital velocity between the Newtonian model and the MOND model, for a binary separation of 0.1 pc, or 2×10^4 AU, is $\sim 50 - 200\,\mathrm{m\,s^{-1}}$, depending on eccentricity.

For precise constraints on gravity in the weak regime, thus, and even in the idealized case of perfect measurements, one should be concerned about any astrophysical effects that may alter the observed velocity difference between the two components of a wide binary to levels comparable to a few tens of $\mathrm{m\,s^{-1}}$. Thus, clearly, **the correct implementation of this test needs to worry first and foremost for the possibility of companions to the components of the binaries used for the test**, as a close-in giant planet or a wide enough substellar companion would be enough to inflate the relative velocity among components, making it appear inconsistent with Newtonian expectations. **In this way, the potential presence of hierarchical triples in the sample, or massive planets hosted by the stars, is by far the most important systematic affecting the gravity test.**

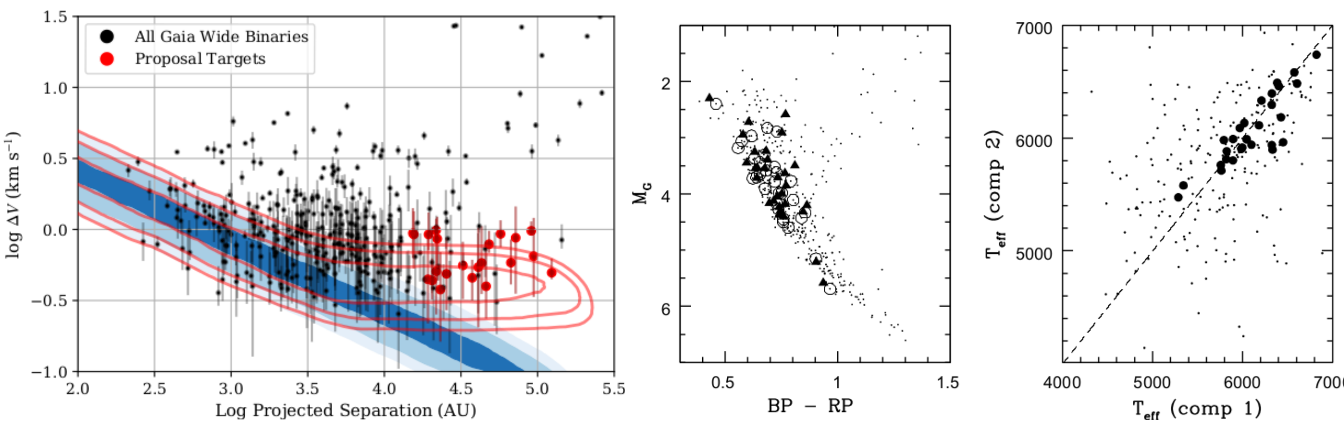


FIGURE 1: LEFT panel: 3D orbital velocities of the components of wide binaries from the catalog of Andrews, Chanamé, & Agüeros (2017), updated with Gaia DR3 astrometry and RVs, as a function of the projected separation on the sky. Blue regions indicate the expectations from Newtonian gravity, and red contours indicate those expected under MOND gravity with no external field effect. The red points with error bars indicate the 21 wide binaries (42 stars) that were monitored during our pilot program. These were the pairs with the best astrometry in DR2, and with projected separations larger than 10,000 AU, thus covering the region where differences between gravity models are largest. **MIDDLE panel**: Color-magnitude diagram of the Gaia wide binaries in our pilot program, showing the locations of the components of pairs (open circles and triangles) with similar luminosities and colors. **RIGHT panel**: The luminosity-color selection criteria described just before produces a sample of targets (filled circles) with analog components, as shown by the correspondence between their estimated temperatures. This helps minimize systematic effects due to stellar structure.

The main task of our program, therefore, is to survey the components of the best wide binaries delivered by Gaia for the presence of close-in companions such as planets, brown dwarfs or low-mass stars. By cleaning the sample from the presence of these companions, the proposed observations will produce a set of wide binaries with isolated components having the most precise determinations of their 3D relative (i.e., orbital) velocities possible with present-day instrumentation, which is exactly what's needed to achieve a reliable test of gravity.

Other sources of systematic biases for the test include: (a) unrecognized pairs belonging to moving groups and stellar streams, as well as recently ionized former binaries, and (b) stellar structure effects. The first ones constitute the contamination that affects any wide binary catalog, and are easily dealt with by restricting to pairs not wider than ~ 1 pc, as shown in our series of papers based on Gaia data itself (Andrews, Chanamé & Agüeros 2017; 2018a; 2018b). Stellar structure effects include the small but finite gravitational redshifts of any stars (of the order of 600 $\mathrm{m\,s^{-1}}$ in the case of the Sun), and the convective blueshifts typical of stars with outer convective envelopes (which can be the size of a couple hundred $\mathrm{m\,s^{-1}}$ for a solar type star). The latter effects are unavoidable, but can be minimized by focusing on the binaries with similar components. In addition, they can also be dealt with statistically by studying the behavior of relative velocities as a function of spectral type. Accounting for these effects, therefore, requires working with a large enough sample that allows statistical corrections.

In this sense, we want to address here a concern from the CNTAC of semester 2022-A, that argued that *"The key point for the success of this proposal is to properly account for such still present errors. Yet the proposal lacks a more convincing explanation of how this will be done. Convection is stochastic, and it is not clear how exactly stars of similar type will help to minimize this effect, or the effect of starspots"*. **The answer to this is precisely the Long Term necessity for this program, as only a monitoring strategy that obtains repeated measurements over adequate timescales can not only get rid of triples, as argued above, but also provides the way to eliminate the temporal stochasticity that is the nature of convection and activity.**

METHODOLOGY AND SAMPLE SELECTION: Gaia's astrometry is the best available and is only going to improve with upcoming data releases. What's left in order to reliably perform the gravity test, **and therefore the immediate objective of this proposal**, is the measurement of the RVs of the components of the binaries to the level of precision discussed above. This is a higher demand in precision than that offered by Gaia's own RVs (with errors $\sim 1-2\ \mathrm{km\,s^{-1}}$ at the magnitudes of our targets). **Therefore, this requirement can only be delivered from the ground using instrumentation specifically designed for extrasolar planet studies.**

Our target selection is illustrated in Figure 1 and its caption. We extract our sample from the TGAS wide binary catalog of Andrews, Chanamé & Agüeros (2017), updated by now with Gaia DR3 astrometry. The full sample used for our pilot program is shown in the $\Delta V - \log s$ space that is the main diagnostic for the gravity test (left panel). This catalog is large and varied, with less than 5% contamination from random alignments. For the gravity test, the ideal Gaia targets are those with the best possible astrometry and RVs, now from DR3, and with projected separations larger than s $\sim 10^4$ AU (shown in red in Figure 1), where the model predictions start to diverge from each other.

We select the highest-quality binaries, pairs whose components have parallax errors < 0.05 mas, proper-motion errors < 0.05 mas/yr, and projected separations $s > 10^4$ AU, where the gravity theories start to diverge. Among those observable from La Silla during 2023-A, we further selected the pairs with the most similar luminosities and colors ($\Delta \mathrm{M_G} < 0.3$ mag and $\Delta(\mathrm{BP}-\mathrm{RP}) < 0.1$ mag, respectively; Figure 1, middle panel), thus favoring binaries with components of similar spectral types, as demonstrated by the resulting approximate correspondence between their effective temperatures (Figure 1, right panel). Finally, we also dropped from our list any binary showing a Gaia source within 10 arcsec of any of its components.

REFERENCES: Andrews, J., Chanamé, J., Agüeros, M., 2017, MNRAS, 472, 675 • Andrews, J., Chanamé, J., Agüeros, M., 2018a, MNRAS, 473, 5393 • Andrews, J., Chanamé, J., Agüeros, M., 2018b, RNAAS, 2, 29 • Gaia Data Release 2, Brown, A., et al., 2018, A&A, 616, 1 • Hernández, X., Jiménez, M., Allen, C., 2012, The European Physical Journal C, 72, 1884 • Hernández, X., Cortés, R., Allen, C., Scarpa, R., 2018, International Journal of Modern Physics D, arXiv:1810.08696 • Pittordis, C., Sutherland, W., 2019, MNRAS, 488, 4740 • Scarpa, R., Ottolina, R., Falomo, R., Treves, A., 2017, International Journal of Modern Physics D., 26, 1750067.

JUSTIFICATION FOR LONG-TERM STATUS

The principal technical goal of the project is to determine the systemic radial velocity (RV) of each of the components of the wide binaries with a precision of the order of few tens of $\mathrm{m\,s^{-1}}$. Therefore, in general terms, the methodology required to achieve these measurements is essentially the same as that used in the detection of extrasolar planets with the RV method. Our co-I Rafael Brahm, who designed the Technical Justification of this program, is a well known leader on this field, and the developer of CERES. What is required for our program to be completed, therefore, is to monitor each star for a long time span (years) in order to fully characterize its level of RV variation. We will need to detect and model periodic and semi-periodic variations produced by planets, close binaries, and/or stellar activity, in order to estimate and subtract them, and therefore obtain the true systemic velocity of the star. **The success of our small (i.e., few epochs in just one semester) pilot CNTAC program (see Current Status) has unambiguously validated the soundness of our strategy.**

A monitoring time of two years is the minimum period for performing the proposed analysis. Fifteen (15) RVs per semester is a typical number of observations if compared to successful exoplanet discovery surveys (e.g., Hébrard et al. 2016, AA, 588, 145). In the proposed two years of observations we will characterize the presence of companions to each of the components of the wide binaries up to a distance of ≈ 2 AU, which corresponds to the distance at which the occurrence rate of exoplanets peaks (Winn & Fabrycky 2015, ARAA, 53, 409). This timespan will also average out the stochastic effects of stellar structure phenomena. The search for companions at even larger separations will be performed with high resolution imaging (please see Current Status) and future Gaia astrometry.

RESPONSE TO 2019-B; 2020-A AND 2021-B TAC COMMENTS

We consider important to address the few concerns expressed by the CNTAC referees on our 2019-B, 2020-B and 2021-B proposals. Please see also page of Current Status.

- *the team should also consider projection effects, which are suggested to cause the observed deviation (El-Badry 2019) at larger separations*: all our measurements of ΔV already include the effect of projection of the tangential and radial velocities at different positions on the sky, and this effect is also accounted for in the left panel of Figure 1. As can be seen, projection effects can be important at large separations, but they are not the responsible ones for the apparent discrepancy between the data and Newtonian predictions at the largest of separations.

- *restricting the sample to separations smaller than 0.2 pc makes the window to differentiate the models become too small*: this was due to an unfortunate choice of words in the 2019-B proposal, and we are not restricting our sample to that separation, but rather selecting only binaries with projected separations from 10,000 AU up to just short of a parsec (red circles in Fig.1). Therefore, we are indeed probing the regime of separations where the models are the most discrepant.

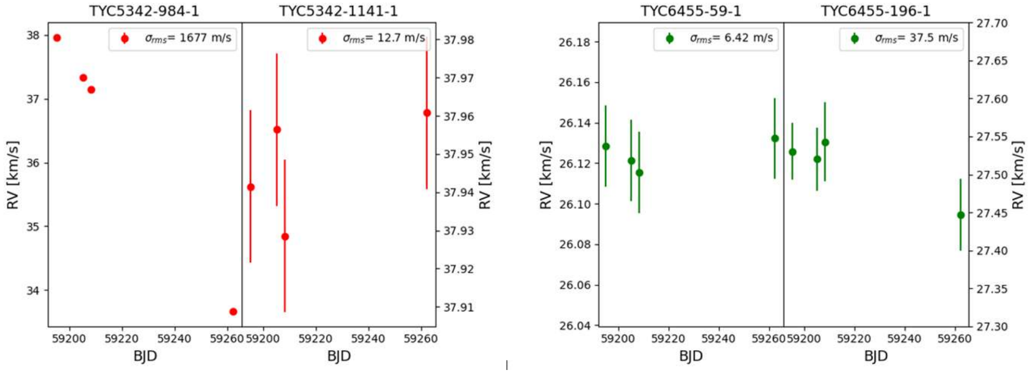
- *1) the genuine binary nature of the farther pairs ($> 10^4 AU$) for this proposal should be (...) questionable. 2) the existing data of the selected sample for this proposal (the red dots) are already enough to justify the correctness of MOND against Newtonian theory*: these two statements are actually incorrect. The data shown in our figures are from Gaia DR3, the best available to anyone, but that does not mean they are free from systematics. If MOND had been already proven correct, ΛCDM would have already fallen, which is not the case. It is extremely well established that the pairs at small separations are true binaries, but their relative 3D velocities are so small that the measurement is not free from systematics, and they appear to deviate from Newtonian predictions. It is precisely the purpose of our program to correct for such systematics.

CURRENT STATUS OF THE PROJECT

This is a completely new project, in the sense that we sent our first proposal on 2019-B, which was not accepted. In the previous section we provided answers to the points in the referee report from 2019-B. Our proposal was resubmitted in semester 2020-A, and the CNTAC awarded 4 nights with FEROS, though the request for Long Term Program was rejected. We deem important to address here the comments raised by the TAC on our 2020-A proposal for a Long Term Program:

- *For the next semester, we expect a proposal for long-term status to include (i) sufficient results from the time awarded to demonstrate the expected single-epoch accuracy for the sample of stars observed*: we carried out a small pilot program, targeting only a few epochs per star, in order to test the precisions we claim and the soundness of our strategy. This is illustrated in the Figure below, which demonstrates the soundness of our program.

- *For the next semester, we expect a proposal for long-term status to include: (iii) if it is decided not to do pre-speckle imaging of the sample prior to the spectroscopy then there must be a clear justification for this decision*: we explored this suggestion by the TAC very seriously, and concluded that, actually, speckle imaging does not help our goals by much, that the requested RV monitoring is indeed the best way to achieve our ultimate goal, and, moreover, that much better than speckle is the option of interferometry. There is no room in this proposal to demonstrate all of the above, but we suggest the TAC to look at our 2020-B proposal, where we do include a detailed explanation aided by a full figure. We thus submitted proposals for near-IR interferometry with the PIONIER instrument on the VLTI, which were accepted and data started to be delivered in December 2020, once operations started to be resumed after the world pandemic hit. Here again, there is no room to provide details of these observations in this space, but we cite here the ESO observing run IDs of our program to demonstrate it exists: 106.21HR.001, 106.21HR.002, 106.21HR.003.



This figure shows two example pairs in our pilot program. We plot RV measurements with FEROS obtained under a total baseline of 2 months, as a function of time. On the left, we have an example where we discover a component that is itself an evident close binary. These are rejected from the monitoring, no matter its companion is stable over these 2 months. On the right panel, a pair with the two components extremely stable over the monitoring period. The scales of the vertical axes, and the preliminary error bars, show the precisions we are able to obtain. Again, this clearly demonstrates our claims and the soundness of the strategy we propose for our Long Term program.

TECHNICAL DESCRIPTION

Co-I Rafael Brahm of this proposal has extensive experience in the use of precision radial velocities to detect extrasolar planets, and is the developer of CERES, the analysis package recommended by the CNTAC for spectroscopic data. Along with co-I Sebastián Vilaza, and experienced user of CERES, they are in charge of measuring the true systemic RVs of the components of the binaries in our sample.

Our final sample consists of 30 wide binaries and hence 60 stars. Figure 1 shows the pilot program sample in various planes. We propose to use the FEROS spectrograph to monitor our 60 stars in a time span of 2 years, taking approximately 15 RV epochs per star per semester. We are obtaining precisions of 20 m s^{-1} or better in each RV, which translates in 300s exposures for a V=12 mag star (faintest magnitude of our sample), and we are setting our minimum exposure time to 120s. By considering the particular magnitudes of each star and by assuming a pointing overhead of 180s per observation, we estimate that our project will require 24h (science observations) + 30h (pointing overheads) = 54h per semester. **Thus we are asking for 6 FEROS nights for each semester.** The code used to filter our catalog through Gaia and to compute the required amount of time has been made public[1]

The observations are performed in the simultaneous wavelength calibration mode, where the secondary fibre is illuminated with a ThAr Lamp in order to trace the instrumental velocity drift during the observations. The data are being processed with the CERES pipeline (Brahm et al. 2017, PASP, 129, 4002) which has been extensively used for discovering exoplanets with FEROS and has proven its ability to reach the 3 m s^{-1} precision for bright stars (Espinoza, Brahm et al. 2020, MNRAS, 491, 2982). The data are being processed as soon as the spectra is obtained and we are able to perform a spectral classification. Just after the first spectrum per star we are being able to identify if the target is effectively suitable for performing the long term study that we propose. For example we can reject targets showing significant rotational velocities ($>$ 20 km s^{-1}). As the RV measurements per star begin to accumulate, we will proceed to model these time series using the recently developed Juliet code (Espinoza, Kossakowski, & Brahm, 2020, MNRAS, 490, 2262) which will allow us to fit Keplerian signals and Gaussian Processes if we identify a signal produced by close orbital companions (planets, brown dwarfs and stars) and/or stellar activity.

One important detail is that in order to have an optimal modeling of the RV signals of our stars, the observations should be performed as homogeneously spread over the semester as possible. **For this reason, if the 6n that we request through CNTAC are awarded, we have an ongoing agreement with researchers from the MPIA where our observing time is being combined with them in order to have a much homogeneous monitoring of our stars and theirs. Please see the attached letter of agreement. We stress that these other MPIA projects are completely unrelated to the scientific goals of our gravity test project, and that we have no means of obtaining MPIA time either.** This possibility of spreading our observations through the semester is not possible with other similar facilities offered by the CNTAC (e.g., CORALIE), and while in principle we could do it with the queue observing mode of CHIRON, the reduced size of the telescope would produce the necessity of a significant number of extra nights to fulfill our goals. These reasons make FEROS the optimal instrument to perform our program.

In a time span of 2 years of observations we will be able to derive the systemic RVs of the components of our wide binaries with a precision of 20 m s^{-1} or better. After these 2 years those stars that present linear or quadratic trends in their RVs won't be used for the final analysis, because these stars will require an even longer monitoring to derive their systemic velocities due to the presence of "long" period companions. On the other hand, those stars that don't present RV trends may be subject of high resolution imaging observations in order to further confirm the absence of "long" period orbital companions that could be accelerating the target star in a longer timescale.

[1] https://github.com/rabrahm/cntac-wbs

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Dear members of the CNTAC,

I am the Principal Investigator of the “Warm gIaNts with tEss (WINE): planet validation with FEROS” program, currently being executed with the FEROS spectrograph on the 2.2m MPIA telescope at La Silla Observatory. The present letter is to certify that I have an agreement with Prof. Julio Chanamé to coordinate the scheduling of FEROS observations for our programs. In case his Long Term Program "A Clean Test of Gravity at Very Weak Accelerations" is approved, we will keep this agreement for the full duration of said program. This will benefit us both by giving us extended flexibility to select the best cadences possible for both programs.

Yours sincerely,

Melissa Hobson (hobson@mpia.de)

Hobson