Final report for DLR project 50OR2214:

Confirming the most massive neutron star with observations of its companion

I. Short Description

1. Task definition

The ultimate purpose of this project is to constrain the unknown behaviour of the strong nuclear force at densities above that of the atomic nucleus, in particular determining how incompressible matter is at such high densities. This can be achieved by measuring a large neutron star (NS) mass. To do so we have been granted 5.2 hours of time on the James Webb Space Telescope (JWST) in Cycle 1 through open-time competition to observe the companions of binary pulsars in the globular cluster NGC6440 with the NIRCam instrument, among which is NGC 6440B (Pulsar B). If we detect a light WD companion to this system, then this pulsar would have the largest NS mass ever measured (about 2.5 solar masses). This would show that matter in the centre of a NS is much more incompressible than predicted by almost all models of super-dense nuclear matter, and point to new physics of the strong nuclear force at high densities.

2. Conditions under which the project was carried out

To timely process and analyse our new JWST data and publish the results, we have requested through the DLR's support on Astronomy and Astrophysics research and been awarded a funding of 1.5 years of full-time work for Dr. Chen, the Co-Principal Investigator (CoPI) of the awarded JWST program. As the success in achieving the science goals of the project requires analysis of complementary radio data and knowledge of stellar populations, our team includes world-class experts in these fields: JWST project PI Dr. Freire and Co-I Dr. Ransom on compact objects and pulsar timing in the radio band, and Co-Is Drs. Pallanca, Cadelano, and Heinke on stellar populations in globular clusters.

3. Planning and execution of the project

The funding of our DLR project started on 1 September, 2022 and ended on 29 February, 2024. The starting date of the funding coincided closely with our JWST observations, which were carried out on 17 August, 2022, ensuring no delay in developing analysis tools, timely progress in publication of the results, as well as planning of the follow-up observations as needed. As will be described in detail in Section II Detailed Description, the grant recipient Chen has carried out the work packages set for the 1.5 years of the funded period, with modification according to the results, in analysing the JWST data, publishing the results, and strengthening the international scientific collaboration.

4. Scientific state of the art:

Neutron stars (NSs) are the remnants of what once were very massive stars. Unlike the massive stars that originated them, NSs are extremely difficult to study, owing in part to their extremely small size, with radii of the order of 10 km. Within this small volume, they contain more mass than that of the Sun, and thus have, in their centres, densities of hundreds of millions of tons per cubic cm, which are significantly larger than the density of the atomic nucleus.

These densities are so large that the state and composition of matter are unknown. This is currently one of the most active topics of research (Ozel & Freire 2016). The lack of detailed knowledge of the microscopic behaviour of matter at these densities translates into a lack of detailed knowledge of its bulk properties, in particular the relation between pressure and density (the equation of state, EoS) of nuclear matter at these densities. This in turn translates into ~ 20 % uncertainties in the knowledge of physical macroscopic properties of NSs, like their radius, tidal deformability, moment of inertia, and the maximum mass of a NS.

An implication of this is that precise measurements of these macroscopic properties of NSs has the potential for constraining the EoS and therefore inform our knowledge of the microscopic state and composition of this super-dense matter. Precise knowledge of the EoS has broad astrophysical applications, like supernova physics and gravitational wave studies, and fundamental physics, like the study of the nuclear force (Lattimer 2021) and tests of gravity theories (Freire & Wex 2024).

Perhaps the most definitive constraints on the EoS to date have come from the measurement of large NS masses, which directly constrain the maximum mass of a NS. There are three reasons for this: first, different EoSs result in widely different predictions for the maximum NS mass, second, NS masses can in some cases be measured very precisely, and finally, these mass measurements are in some cases model-independent, for instance, when they are derived from the *timing* of the radio pulsar, where the only assumption made is the validity of general relativity, which has been tested exquisitely in this regime (Kramer et al. 2021, Freire & Wex 2024).

Thus far, the largest NS mass derived from timing is that of PSR J0740+6620 (Fonseca et al, 2021), which has a mass of 2.08+/- 0.08 solar masses, from the relativistic Shapiro delay (Shapiro, 1964) measured in the timing of this pulsar. Knowledge of the existence of such massive neutron stars has had a very large impact in many fields of research.

The target of this proposal:

PSR J1748-2021B is one of the five pulsars found in the globular cluster NGC 6440 using the 2 GHz ("S-band") receiver of the Green Bank Telescope (GBT) in West Virginia, USA (Freire et al. 2008). It has a spin period of 16.76 ms, an eccentric ($e = 0.57$), wide (20.55-day) orbit. The nature of the companion is unknown, but it is likely to be much less massive than the pulsar: the semi- major axis of the pulsar's orbit, projected along the line of sight to the Earth, is 4.466 light seconds, which results in a minimum companion mass of about 0.1 solar masses.

The large orbital eccentricity allowed, with continued timing of the pulsar signal, a highly precise measurement of the rate of advance of the periastron of the system. Assuming this is an effect of general relativity (an assumption that is backed up by the results of this project), this implies a total mass of 2.92 +/- 0.15 solar masses. This is compatible with the system masses for regular double neutron star systems. However, if the companion is a neutron star, it would likely have a mass of about 1.4 solar masses. This would imply that the system is being seen with an orbital inclination of 4.8 degrees, which is rather unlikely. If the system is edge-on (a much more likely situation), then the companion mass would be 0.117 solar masses, and the pulsar mass would be close to 2.8 solar masses. An average over all possible orbital inclinations yielded a pulsar mass of 2.74 +/- 0.20 solar masses (Freire et al. 2008). These results have been confirmed by subsequent timing with the GBT telescope and with MeerKAT (Ransom et al. 2024, in prep, Venkataraman Krishnan et al. 2024, in prep).

Such a large pulsar mass would represent a complete revolution in our knowledge of the properties of super-dense matter. However, lower masses cannot yet be excluded, because, apart from the lower probability, nothing excludes them. In particular, the recent radio timing of this pulsar has not detected any additional relativistic effects in the orbit, and therefore no measurements of the mass of either the pulsar or the companion.

In several other binary pulsars in globular clusters, the identification of the companions at optical and near-infrared, and detailed photometry, has resulted in relatively precise mass measurements (e.g., Rivera-Sandoval et al. 2015, Cadelano et al. 2015). For this reason, we looked for the companion of PSR J1748-2021B in archival Hubble Space Telescope (HST) data (Pallanca et al. 2019). No companions were clearly detectable, but WD companions to pulsars could well be below the HST detection limit, especially as the host globular cluster (NGC 6440) is highly obscured by intervening dust. This motivated our JWST time request, which, as expected, revealed much fainter stars in this cluster.

References:

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Shapiro 1964, PRL, 13, 789

5. Cooperation with other bodies
This project involves an international scientific network as it is assisted by our collaborators in the United States (NRAO), Canada (University of Alberta), Italy (INAF) and the United Kingdom (University of Manchester). As aforementioned the success of our JWST project requires both analysis of JWST and radio data. The specific collaborations are the following. The analysis of radio data is led by JWST project PI Freire (MPIfR, Germany) and Co-Is Ransom (NRAO, USA) and Stappers (University of Manchester, UK). The science collaboration to interpret the JWST results and to compare with model prediction includes JWST project Co-Is Pallanca, Cadelano, (INAF, Italy), and Heinke (University of Alberta, Canada).

II. Detailed Description

Our JWST observations were carried out on 17 August, 2022 and the data have been processed, analyzed, and published during the 1.5-year of the funded period, with the grant being used to support full-time work for Dr. Chen. We summarize below the necessity and relevance of the work carried out in each work package WP (one for every 3 months) and the needed modification according to the results from the data. The most important scientific/technical results, including the new and planned publication, are also listed in the relevant WPs. Afterwards we describe the expected benefit in the updated utilization plan, the progress in the field relevant to the project, and the publication.

WP1.1: as specified for Month 1-3 in the original application, I have carried out the measurement of multi-band stellar photometry from dithered tiles and the construction of a master photometric catalog of stars. I further improved our strategy on flux measurement of the companions of pulsar binaries and their neighbouring stars. The point spread function (PSF)-fitting photometry is applied not only on the combined image produced by stacking individual dithered tiles in the same band to create well-sampled PSFs, but also on individual dithered tiles. The purpose is to search for the possible flux variability in the companions of pulsar binaries as an additional supporting evidence for them being in the pulsar binary systems.

WP1.2: as specified for Month 4-6 in the original application, I have made precise estimates of extinction correction toward the regions where the pulsar binaries are located using the four-band photometry from our JWST observations and the additional 2-band photometry from the previous HST data. The HST photometry was provided by our co-investigator in the JWST proposal, Dr. Pallanca (INAF, Italy). The combined 6-band photometry of the matching stars is used to construct their spectral energy distributions and to derive the precise extinction correction across the region. This improves the inferred intrinsic colors and magnitudes as well as mass estimates of the stars when compared with the modelled colours and magnitudes from stellar isochrones and evolutionary tracks.

WP2.1: this WP was moved up to Month 7-9 before WP1.3 (which was set originally for Month 7-9) to assess the need of follow-up JWST observations of NGC6440B. I have improved the astrometry of JWST images using the high-precision position of Pulsar D from radio timing. As expected we detected the companion of Pulsar D in the JWST NIRCam images. Using the 0.02" position accuracy of Pulsar D from radio timing together with overlapping sources from GAIA DR3, we improved the pipeline-processed JWST images which have a typical position uncertainty ~0.3". This is critical as the stellar field around Pulsar B is crowded and an accurate astrometry is the key to unambiguously identify the pulsar companion. Despite the accurate astrometric link, we do not detect the companion of Pulsar B in our ultra-deep JWST images.

WP1.3 and WP3.1 for Month 10-12 and 13-15: WP3.1 was moved before WP2.2 (which was set originally for Month 13-15) for a timely publication before submitting a new observation proposal for the JWST's Cycle 3 open time competition. We have identified distinct stellar populations, i.e., the upper and lower main-sequence splits, of NGC6440 using our JWST data. With the JWST's unprecedented angular resolution and sensitivity, for the first time both splits above and below the characteristic knee on the main sequence are detected clearly in a globular cluster, indicating multiple stellar populations with variations in helium and water abundances. It opens a new window for future investigations of multiple stellar populations in bulge globular clusters in the Galaxy. The paper is led by our Co-I Drs. Cadelano and Pallanca (INAF, Italy, who are experts of globular clusters) and is the first publication of our project. It is published in the Letter of Astronomy and Astrophysics Journal (DOI:10.1051/0004-6361/202347961) and the support from this grant is noted in the acknowledgement. This paper is searchable through the grant recipient Chen's ORCID: 0000-0002-3925-9365.

WP2.2 for Month 16-18: we are preparing the manuscript of the second paper on companions of three binary pulsars B, D, H in NGC6440. As aforementioned, despite the accurate astrometric link, we do not detect the companion of Pulsar B in our ultra-deep JWST images. The non-detection rules out the possibility of the companion being a main-sequence MS star: any MS star with a mass larger than 0.12 solar mass (the lowest allowed by the orbital parameters of the system) should be detectable in our images. This implies that the companion is a compact object: either a white dwarf (WD) or NS.

Nonetheless, the demonstration that the companion is a compact object has one positive implication, which is the confirmation that the advance of periastron measured via radio timing in the NGC 6440B system is of relativistic origin. This confirms the total mass of the binary estimated from that effect (the aforementioned value of 2.69 solar masses) with the assumption of the validity of GR. These results are also important for further time requests with MeerKAT and the future Square Kilometer Array, since measuring additional relativistic effects (especially the Shapiro delay) is the only way to determine the masses of individual components in this pulsar binary system and to test if Pulsar B is the most massive NS known.

The manuscript of the second paper on companions of three binary pulsars is planned to be circulated among co-Is of the JWST project for contribution and comments in September 2024 and submitted to the Astronomy and Astrophysical Journal in October 2024 after approval from all co-authors. The support of this grant is noted in the acknowledgement and will be searchable with grant recipient Chen's ORCID when it is accepted for publication.

The expected benefit regarding the usability of our results in terms of the updated utilization plan:

1. Inventions/property rights:

The work being funded is purely concerned with fundamental research, and does not include the development of any new marketable items or technologies. The JWST pipeline processed data products are already available on the JWST archive, as our data have become public after one year of the proprietary period. Additional databases and data products combining both HST and JWST data made during this work are to be made publicly available when the relevant paper is accepted and published.

2. Economic prospects of success:

This is described as in the above item.

3. Scientific/technical prospects of success:

During the length of our project, our first paper has been published, and our JWST images were chosen as the ESA/Webb picture of the Month that is released for the general public from 2024.05.01 on with the following link https://esawebb.org/images/potm2404a/ . This provides an excellent opportunity for outreach and publicizing our results. After the end of our project (on 2024.02.29), we will additionally (1) make presentations of results in scientific meetings, (2) make our catalogs/database as well as the computational algorithms publicly accessible upon the acceptance of our scientific papers.

This research enhances our scientific network, as aforementioned in Section I Short Description the results were assisted by our collaborators in the United States (NRAO), Canada (University of Alberta), Italy (INAF) and the United Kingdom (University of Manchester).

4. Scientific/economic connectivity:

Our results on the discovery of main-sequence splits of low-mass stars in NGC 6440 (Paper I) represent an unprecedented study of the multiple stellar populations of this and other globular clusters, hitherto inaccessible to any telescopes.

Our results on pulsar binaries (Paper II) determine the nature of these companions and establish that the companion of NGC6440B being a compact object. Although its non-detection is disappointing (because we are not able to determine the precise nature of the companion and estimate its mass, and thus the mass of the pulsar), we are able to derive an upper limit for the mass of the pulsar of 2.49 solar masses. Furthermore, the compact nature of the companion that is implied by our data indicates that the periastron advance measured in the radio timing of the pulsar is relativistic, confirming the total mass of the system estimated from this effect. Furthermore, this is also essential for further radio timing requests with MeerKAT and Square Kilometer Array as measuring additional relativistic effects is the only means to determine if NGC6440B is the most massive neutron star, which would have a fundamental impact on studies of neutron star astrophysics, dense nuclear matter, and the fundamental properties of the strong nuclear force.

Beyond the end of the period being funded, we expect both papers will lead to very substantial scientific follow-up in the aforementioned areas of research.

The third-party progress in the field become known during the funded period that are relevant for implementation of the project:
I have used archival HST data to make a contribution to a paper on the companion of the binary pulsar in NGC1851E. It is a possible millisecond pulsar - black hole companion, as it has a mass between 2.09 and 2.71 solar masses. If it is not a black hole, it could be a very massive neutron star, with a mass similar to the upper mass estimate for NGC 6440B, which we targeted with the JWST. Our study of NGC 1851E have the potential to illustrate how objects in the compact object mass gap (between the highest measured neutron star masses and the lowest measured black hole masses) might form. This paper, of which I am a co-author and have included the grant number in the acknowledgement, has been published in the Science Journal (DOI: 10.1126/science.adg3005).

In addition to the fields of globular clusters and companions of pulsars, I have also used archival Spitzer data and ground-based optical imaging data to make a contribution (with my expertise in optical and IR analysis on stellar populations) to three papers on massive star formation and star formation history in the Large Magellanic Cloud, a nearby satellite galaxy to our Milky Way Galaxy. These projects help understand star formation processes in different environments as well as uncover the underlying star formation history, which help illuminate how different properties of stars are formed that could lead to formation of very massive binary pulsars like our project target NGC6440B and the aforementioned NGC1851E. These three papers, of which I am a co-author and have included the grant number in the acknowledgement, have been published in the Letter of Astronomy and Astrophysics Journal (DOI: 10.1051/0004-6361/202348017), the Astrophysical Journal (DOI: 10.3847/1538-4357/acf5ed), and the Astronomy and Astrophysics Journal (DOI: 10.1051/0004-6361/202347364).

The publication:
We maintain the goals of two publications of this project as stated in the revised application that was approved for 18 months of funding, i.e., one publication during the funded period and the other after the end of the project. The first paper, the JWST discovery of the main-sequence splits in NGC6440, has been published (with details listed in WP1.3 and 3.1 in Section II). The second paper on companions of the three binary pulsars is in preparation (with details listed in WP2.2 in Section II).

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18. Kurzfassung

Ziel des Projekts ist es, das unbekannte Verhalten der starken Kernkraft bei Dichten oberhalb der des Atomkerns, insbesondere den unbekannten Zustand und die Zusammensetzung der Materie bei diesen hohen Dichten, durch die Messung der Masse eines (möglicherweise sehr massereichen) Neutronensterns, PSR J1748-2021B (Pulsar B unten) im Kugelsternhaufen NGC 6440, einzugrenzen. Aus einem relativistischen Effekt, der in einer Radiozeitreihenmessung bestimmt wurde, haben wir ermittelt, dass die Gesamtmasse des Systems 2,92±0,15 Sonnenmassen ($M_\odot$) beträgt. Eine statistische Analyse deutet auf eine wahrscheinliche Pulsarmasse (PM) von 2,74±0,20 $M_\odot$ hin, die, falls sie sich bestätigt, eine Revolution in unserem Verständnis des unbekannten Zustands der Materie bei supranuklearen Dichten darstellen würde (z. B. Özel & Freire 2016). Die Massen der einzelnen Komponenten lassen sich jedoch noch nicht aus der Radiozeitreihenmessung bestimmen. Ein möglicher Weg, sie zu messen, ist der Nachweis des Begleitsterns bei optischen/nahen IR-Wellenlängen. Wir haben daher 5,2 Beobachtungsstunden am JWST in Zyklus 1 zur Verfügung gestellt bekommen, um Pulsar B mit dem NIRCam-Instrument zu beobachten. Wenn wir den Begleitstern des Pulsars in den NIRCam-Bildern entdeckt und festgestellt hätten, dass es sich, wie vermutet, um einen massearmen Weißen Zwergstern handelt, hätten wir seine Masse aus der Multiband-Photometrie abschätzen und somit die PM bestimmen können. Um unsere neuen JWST-Daten zeitnah zu verarbeiten, zu analysieren und die Ergebnisse zu veröffentlichen, haben wir im Rahmen der DLR-Förderung für Astronomie und Astrophysik eine Finanzierung von 1,5 Jahren erhalten. Trotz der deutlich verbesserten Empfindlichkeit des JWST wurde der Begleiter von Pulsar B in unseren Bildern nicht entdeckt. Dies deutet darauf hin, dass es sich nicht um einen regulären Hauptreihenstern, sondern, wie vermutet, um ein kompaktes Objekt handelt. Die Nichtentdeckung bedeutet, dass wir die Masse des Begleiters nicht eingrenzen können und somit noch nicht nachweisen können, dass Pulsar B der massivste je entdeckte Neutronenstern ist. Zusätzlich zur Identifizierung des Begleiters von Pulsar B haben wir nach Begleitern für vier weitere Doppelpulsare in NGC 6440 gesucht und den Begleiter von einem von ihnen (Pulsar D) entdeckt. Darüber hinaus haben wir die Massen und das Alter der stellaren Population im Zentrum von NGC 6440 veröffentlicht. Dies beinhaltet eine noch nie dagewesene Studie der massearmen (0,12 - 0,5 $M_\odot$) Sternpopulation in einem Kugelsternhaufen, die bisher für alle Teleskope unzugänglich war.

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18. Abstract
The ultimate purpose of the project is to constrain the unknown behaviour of the strong nuclear force at densities above that of the atomic nucleus, in particular the unknown state and composition of matter at these high densities, by measuring the mass of a (potentially very massive) neutron star, PSR J1748−2021B (pulsar B below) located in the globular cluster NGC 6440. From a relativistic effect measured in radio timing, we have determined that the total mass of the binary is 2.92 ± 0.15 solar masses ($M_\odot$). A statistical analysis indicates a likely pulsar mass (M_P) of 2.74 ± 0.20 $M_\odot$, which if confirmed would be a revolution in our understanding of the unknown state of matter at supra-nuclear densities (e.g., Özel & Freire 2016). However, the masses of the individual components cannot not yet be determined from radio timing. A possible way of measuring them would be to detect the companion star at optical/near IR wavelengths. We have thus been granted 5.2 hours on the James Webb Space Telescope (JWST) in Cycle 1 to observe pulsar B with the NIRCam instrument. If we detected the pulsar's companion star in the NIRCam images and found that, as suspected, it is a low-mass white dwarf star, then we would have been able to estimate its mass from multi-band photometry and hence determine the M_P. To timely process and analyse our new JWST data and publish the results, we have been granted a funding of 1.5 years through the DLR's support on Astronomy and Astrophysics research. Despite the much improved sensitivity provided by the JWST, the companion of pulsar B was not detected in our images. This indicates that it is not a regular main-sequence star but, as suspected, a compact object. The non-detection implies that we cannot constrain the mass of the companion and thus we cannot demonstrate that pulsar B is the most massive neutron star. On the positive side, this implies that the total mass of the system inferred from the rate of advance of the periastron is correct.
In addition to the identification of the companion to pulsar B, we have looked for the companions to four other binary pulsars in NGC 6440, detecting the companion to one of them (pulsar D). We have, in addition, published the masses and ages of the stellar population in the centre of NGC 6440. This includes an unprecedented study of the low-mass (0.12 - 0.5 $M_\odot$) stellar population in any globular cluster, which has until now been inaccessible to any telescopes. Using our JWST data, we have identified distinct stellar populations, i.e., upper and lower main-sequence splits of NGC6440 and published our first paper of the project.

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