Space Astrophysics White Paper for the Mid-Term Review of the 2015-2025 Australian Decadal Plan in Astronomy

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Summary and recommendations

Space is a rapidly evolving field with significant opportunities that were not fully anticipated in the Decadal Plan. The science and technology landscape is being transformed because of new emerging capabilities of low-cost nano-satellites with sufficient power, down-link capabilities and attitude control accuracy to carry space telescopes and other astrophysics payloads, as demonstrated by a ten-fold increase in the number of SAO/NASA Astrophysics Data System entries including "Cubesat" in their abstract from 2011 (21 papers) to 2018 (207 papers). Furthermore, the Australian sector is finally well positioned in this trajectory of rapid global growth thanks to a newly established Space Agency, which may open both strategic opportunities to participate in international projects, and pathways to fund construction of instrumentation for space telescopes. This will likely result in an increased utilization of space facilities for research in Australia, which was already substantial in 2014 (30% for optical/infrared astronomy and 13% across all astrophysics publications). Thus, to maintain and grow the Australian impact in Astronomy through space-enabled research, the key recommendations of this paper are:

1. Iterate the original Decadal Plan recommendation for the "formation of a national body that supports co-ordination of engagement with space-based telescopes";
2. Include support for operations of Australian-led astrophysics missions among the portfolio of activities and projects that receive astronomy NCRIS funding. Decisions on funding should be based upon competitive peer-review that takes into account national and international impact and strategic value for the Australian community;
3. Consider the creation of a mechanism to enable effective participation in international space-based projects for Australian teams, modeled on NASA's "Missions of Opportunity" stream, and aimed at leveraging areas of strength of Australian astronomy, such as technical instrumentation contributions, provision of ground-segment services from a unique geographical location, and/or establishment of science data centers;
4. Strengthen the engagement with the Space Science community and with the National Committee for Space and Radio Science to identify opportunities for cooperation and collaboration, aiming in particular at leveraging cross-disciplinary expertise in space missions, applications in Space Situational Awareness, as well as ionospheric and space weather research enabled by existing and future low frequency radio telescopes, such as the SKA.

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Introduction: The growing importance of Space facilities in global astronomy

Space telescopes, unaffected by atmospheric absorption/emission and wave-front distortion, have been key drivers of scientific progress in astronomy in the last three decades. Observations from the Cosmic Background Explorer satellite and the Hubble Space Telescope led to the 2006 and 2011 Physics Nobel prizes, and future advances are becoming critically more reliant on access to space to collect data across all range of the electromagnetic spectrum as an effective strategy to enable multi-messenger investigations.

The impact of space telescopes in global astronomy can be highlighted by comparison of the scientific productivity of the Hubble Space Telescope (HST) to that of ESO's Very Large Telescope (VLT), two observatories operating at a similar range of wavelengths. Over its lifetime, HST data resulted in over 15,000 scientific papers, attracting in excess of 700,000 citations[2], with an average of more than 800 papers published per year between 2011 and 2017. Data from the VLT produced approximately 600 refereed papers per year in the same period, and only recently ESO's total publication rate exceeded 1000 papers per year thanks to the rapid growth of ALMA-based studies[3]. In this context, Australian astronomy is already depending significantly on access to space. In fact, research undertaken for the Decadal Plan preparation identified that 13.6% of all astronomy and astrophysics research output co-authored by Australian scientists in 2014 was based on a space-based facility[4]. The same study highlights that UV/Optical/IR International Space-based research was the among the most productive areas (10.1% of total publications), at a level comparable to Theory Computational (13%) and Optical/IR 6-10m-class facilities (10.4%).

Upcoming international flagship missions such as the James Webb Space Telescope (JWST), WFIRST, ATHENA, LISA, as well as a range of medium-scale projects (with a budget of order one billion dollars) such as EUCLID, PLATO and ARIEL, will contribute critically to advance all the themes identified in the Australian Decadal plan, ranging from the investigation of the first light sources and the epoch of reionization to the discovery and characterization of Earth-like exoplanets. These facilities will have strong synergy with ground-based observatories where there is either Australian leadership or participation like the Square Kilometer Array (SKA) and the Giant Magellan Telescope.

In addition to these large and ambitious missions, characterized by a budget that makes it challenging to pursue Australian engagement beyond science team membership and/or participation to calls for general observer proposals, new opportunities to develop space telescopes are emerging thanks to the rapid progress in the technology of Cubesats, that is nanosatellites of standardized dimensions and comparatively low cost (~$1-10 million). The field has been transformed since the preparation of the Decadal plan: While prior to 2014 the best CubeSat attitude accuracy was ~30"[5] making such small satellites unsuitable for essentially all astronomy applications, in 2018 the ASTERIA 6U CubeSat demonstrated sub-

[2] https://www.nasa.gov/mission_pages/hubble/story/index.html (statistics at 12/2018)
[3] https://www.eso.org/public/australia/blog/how-productive-is-the-vlt/
[4] https://www.science.org.au/files/userfiles/support/reports-and-plans/2015/australian-astronomy-publication-and-facilities-survey.pdf
[5] National Academies of Sciences, Engineering, and Medicine. 2016. Achieving Science with CubeSats: Thinking Inside the Box. Washington, DC: The National Academies Press. doi:10.17226/23503

arcsec pointing stability while observing bright stars for transiting exoplanet photometry[6]. ASTERIA illustrates how CubeSats have the potential to provide leap-frogging technological capabilities at a fraction of the cost of traditional space missions, making them a particularly attractive option for the Australian community which lacks access to funding streams of large Space Agencies such as NASA and ESA. The emergence of interest in astronomy nanosatellites is quantitatively demonstrated by the rapid growth of publications associated with the field. A bibliographic search with the SAO/NASA Astrophysics Data System returns 843 entries in its library that include the word "Cubesat" in the abstract. Remarkably, approximately a quarter of them (207) where published last year (January to December 2018), which represents a ten-fold growth compared to the 21 Cubesat abstracts in 2011.

Beyond astronomy from space, Australia has a long history of supporting space activities with ground-based facilities, and of technology development in astronomy that translates to space. Australia occupies a unique geographical position and has some of the world's best sites for radio telescopes, making it an ideal location to host ground-stations both for near-Earth and deep space communications. Both NASA and ESA have deep-space communication facilities in Australia, operated by CSIRO.

The Square Kilometre Array (SKA) and its precursor telescopes, ASKAP and the MWA, have spawned a number of lines of research with applicability to Space science. The SKA will operate at low frequencies and can access unique information on the Earth's ionosphere and space weather as a by-product of astrophysical investigations.

All these aspects highlight the opportunity to consider a growth of support for space-based astronomy and astrophysics in the mid-term review of the Decadal plan.

State of the field and opportunities for Australian astronomy

Space-based astronomy is contributing, or has the potential to contribute, to all six key research questions identified in the Decadal Plan. Impact from facilities such as HST, JWST, TESS and PLATO is already highlighted in the Decadal Plan, including the 30% contribution of space-based facilities to the scientific production of optical/infrared astronomy in the country during the decade preceding the preparation of the document.

Emerging opportunities related to either large international missions or exploitation of (small) satellite capabilities that were not considered at the time of the Decadal Plan include:

- Synergy between MWA and SKA radio observations of the intergalactic gas during the epoch of reionization with wide-area deep infrared observations with space-based telescopes such as WFIRST that will map the large scale structure of the sources of ionizing radiation and enable cross-correlation of the multi-wavelength datasets. As only a fraction of the area observed by WFIRST might have the sufficient depth for such study, it would be highly beneficial to ensure coordination between the science teams regarding the choice of deep fields. Furthermore, satellites in lunar orbit could benefit from a radio-quiet environment on the far side which would be ideal for low-wavelength radio astronomy;

[6] https://ui.adsabs.harvard.edu/abs/2018cosp...42E1782K/abstract

- Efficient identification of Gamma Ray Burst (GRB) afterglows originating during the epoch of reionization through rapid infrared photometric follow-up of gamma-ray transients identified by satellites such as the Neil Gehrels Swift Observatory or the upcoming France-China SVOM mission. GRBs represents cutting-edge opportunities to characterise the star formation history of the Universe back to the epoch of reionisation, to measure the chemical composition of intergalactic gas in the early Universe, and the escape fraction of ionizing radiation from galaxies (Chen et al. 2007), which is one of the most challenging, yet fundamental, astronomical measurements. GRBs have distinct advantages as cosmological probes over quasars, as the latter carve out large ionised bubbles within their local environments;
- Measurement of the Cosmic Infrared Background (CIB) and Zodiacal Light. Just as the Cosmic Microwave Background radiation encodes the astrophysics of the aftermath of the Big Bang, the CIB contains the entire integrated history of nearly everything that has happened since the formation of stars. The CIB directly probes the integrated impact of galaxy formation and evolution: star-formation, supernova, stellar evolution, dust production, and supermassive black hole emission. Measuring it directly requires a space telescope to avoid the highly variable infrared glow of Earth's atmosphere. An absolute measurement of the CIB requires accurate modeling and subtraction of the Zodiacal Light foreground, but would be highly complementary to the angular fluctuation CIB measurements from the upcoming SPHEREx NASA space mission;
- Search for other Earths. A major focus of exoplanetary science is the discovery and characterization of potentially habitable Earth-size planets, especially around cool stars where they are more readily detected. Space observations are crucially needed because ultra-stable photometry is required. Several medium to large scale international missions are ongoing, but the field presents significant opportunities for impact with small aperture telescopes at (near) infrared wavelengths, provided that the optics and camera are optimized for ultra-stable photometric accuracy (at the level of a 300-400 parts per million) and that effective strategies for active thermal management are designed;
- Progenitors of fast radio bursts. Radio interferometers, such as ASKAP are now able to pinpoint fast radio bursts to precisions better than 0.1”, identifying not only host galaxies, but also the burst origin within its host. This provides the opportunity to investigate the progenitors through characterization of the environment in which bursts are produced. Detailed studies of these environments at UV/optical/IR wavelengths benefit from comparable resolution to radio observations, and this can currently be achieved only through diffraction-limited space-based international facilities;
- The sky at high energies and its variability. X-ray and gamma ray astrophysics relies critically to space-based observatories, and new opportunities are becoming available. These include constellations of nano-satellites to monitor for GRBs and Gravitational Wave counterparts, as well as flagship space telescopes such as eRosita, which will provide increased spectral and spatial resolution across the whole sky to map galaxy clusters, active galactic nuclei, and supernova remnants.

In addition to the science-driven opportunities discussed above, Australia hosts world-class instrument groups in both optical and radio frequencies. With greater engagement in space-based astronomy comes the chance to apply Australian astronomical instrumentation expertise to space telescopes, contributing to both nano-satellite payloads as well as to larger-scale international missions.

Australia has growing expertise in multi-wavelength and multi-messenger data processing and analytics for astronomy. As telescopes such as ASKAP, SKA and LSST come on line, provision of large-scale archives and associated processing are increasingly critical to effective science. Other papers for this mid-term review are considering the direction of data processing and management, but we note that Australian-hosted archives of data from space-based telescopes would be complementary to the planned activities in optical, radio and gravitational wave domains.

Finally, Australia's ground-based astronomical capabilities have contributed over decades to the success of international space missions, notably CSIRO-run radio telescopes providing tracking services. CSIRO has now expanded such activities by virtue of its role in operating NASA and ESA facilities in Canberra and New Norcia, respectively. With Australia hosting the SKA and SKA precursors, opportunities to continue dual-use of astronomical facilities and the translation of astronomical technologies into space applications are significant:

- Continued use of radio telescopes for ground station services, to augment core NASA and ESA facilities, is possible. For example, the University of Tasmania radio astronomy facilities are being upgraded by the Australian Space Agency to provide uplink and downlink services. Such opportunities exist across Australia's radio astronomy portfolio. Moreover, leading Australian technologies in optical communications connected with astronomy, and radio astronomy technologies such as Phased Array Feeds, can lead to novel concepts for next generation ground stations;
- The global resurgence of low frequency radio astronomy due to the pursuit of the Epoch of Reionisation (EoR), and Australia's role in hosting the low frequency SKA and its low frequency precursor, the MWA, opens several space science opportunities. At low frequencies, radio signals received on Earth are affected by the ionosphere and the ionised plasma due to the solar wind. The MWA has already gained unprecedented views of the solar wind via the technique of interplanetary scintillation and the Earth's ionosphere, while undertaking astrophysical investigations of the Epoch of Reionization and surveys of high redshift radio galaxies, respectively. Thus, astrophysical and space science outcomes are intimately connected via low frequency radio telescopes. The low frequency SKA will provide orders of magnitude improvements over the MWA, with the potential to produce data products of global significance for the space weather community.

Community coordination and support: Recommendations

Space astrophysics and ground-based support of activity in space present a unique set of challenges, as instrumentation needs to be designed robustly, and tested comprehensively, even though nano-satellite projects generally accept a higher level of risk compared to flagship international projects such as JWST. This also includes developing robust flight software to control the spacecraft and the science payload, as well as having accessible and cost-effective infrastructure to operate assets. Thus, access to expertise in lessons learned from national and international experts is critical for effective growth in the field. Relatively smaller projects such as nanosatellites can be used effectively to build sovereign capabilities for future technical participation and leadership in ambitious missions, as advocated by the National Research Infrastructure Roadmap.

To achieve success, coordination and cooperation among the community is needed as no single scientist or small team can succeed in isolation. Therefore, we iterate the original Decadal Plan recommendation for the “formation of a national body that supports co-ordination of engagement with space-based telescopes”. Furthermore, there would be an even greater benefit from strengthening the engagement with the Space Science community and with the National Committee for Space and Radio Science to identify opportunities for cross-disciplinary cooperation and collaboration, aiming in particular at leveraging existing expertise in space mission design and operations, the connections between astronomy and ionospheric science and space weather, and the pursuit of an Australian nationally coordinated Space Situational Awareness (SSA) capability. In fact, existing radio telescopes, SKA precursors, the SKA itself, and a range of optical facilities in Australia can be utilised for SSA, the detection and tracking of objects in Earth orbits (also including an awareness of space weather). With the increasing congestion of the orbital environment, all international agencies have a strong interest in SSA. Australian astronomical facilities could be a significant contributor to international SSA activities.

Successfully building and launching a space telescope is not sufficient to reap the benefit for astronomical progress. In fact, Australian astronomers should also be placed in the conditions to effectively operate Australian-led missions, as well as to be competitive on the world stage in the analysis of space-based data. Therefore, we recommend to include support for both construction and operations of Australian-led astrophysics missions among the portfolio of activities and projects that receive astronomy NCRIS funding. Decisions on funding should be based upon competitive peer-review that takes into account national and international impact, as well as strategic value and participation by the Australian community.

Furthermore, it would be highly beneficial to consider the creation of a mechanism to enable effective participation in international space-based projects for Australian teams, modeled on NASA’s “Missions of Opportunity” stream, and aimed at leveraging areas of strength of Australian astronomy, such as technical contributions (already proven in the area of ground-based instrumentation), provision of ground-segment services from a unique geographical location, and/or establishment of science data centers.

Finally, we note the current role of the Australian Space Agency in several of the areas considered above, including facilitating engagements with its international counterparts such as ESA and NASA, growing ground-based facilities (mission control, tracking stations), and through their working group to develop a national roadmap for SSA, already involving astronomers. However, the Agency is currently focused on industry growth, rather than science. Other mechanisms may therefore be needed to take forward co-ordination on behalf of the Australian community and reflective of the Decadal Plan priorities.