The Heliophysics and Space Weather Open Knowledge Network: The Convergence Hub for the Exploration of Space Science (CHESS)

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November 24, 2022

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Abstract

The growing scale of Earth and space science challenges dictate new modes of discovery–discovery that embraces cross-disciplinary interactions and links between communities, between data, between technologies. Nowhere is the challenge more pressing than in the field of Heliophysics where solar energy is generated, propagated through interplanetary space, interacts with the Earth's space environment, and poses immediate threat to our technological infrastructure and human-natural systems (i.e., space weather). We will present a new project within the National Science Foundation Convergence Accelerator program that represents this new mode of discovery "The Convergence Hub for the Exploration of Space Science (CHESS)." Our approach is to semantically link Heliophysics data through a Knowedge Graph/Network (KG). The presentation and discussion will focus on: - What is a knowledge graph (KG)? - In what ways are KGs poised to transform Earth and space science? - The Convergence Hub for the Exploration of Space Science (CHESS) project and bridging to metadata and knowledge architecture efforts in Heliophysics We will highlight linkages to the NSF EarthCube program and ongoing efforts in the geoinformatics and data science communities across e.g., NSF, NOAA, and NASA.

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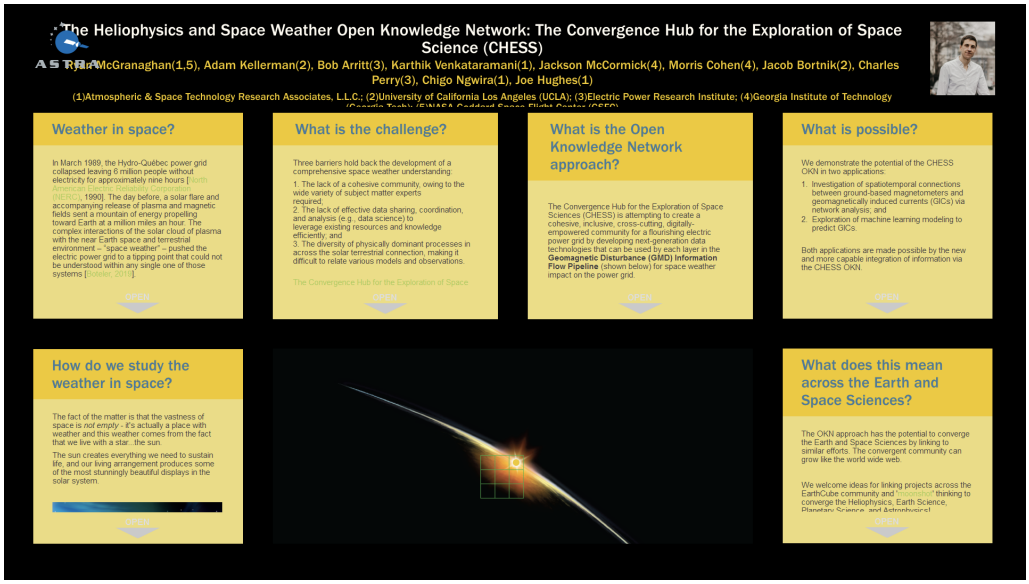

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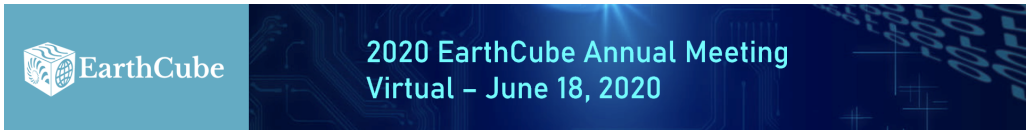


WEATHER IN SPACE?

In March 1989, the Hydro-Québec power grid collapsed leaving 6 million people without electricity for approximately nine hours [North American Electric Reliability Corporation (NERC) (https://www.nerc.com/Pages/default.aspx), 1990]. The day before, a solar flare and accompanying release of plasma and magnetic fields sent a mountain of energy propelling toward Earth at a million miles an hour. The complex interactions of the solar cloud of plasma with the near Earth space and terrestrial environment – "space weather" – pushed the electric power grid to a tipping point that could not be understood within any single one of those systems [Boteler, 2019 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019SW002278)].

The catastrophic events of 1989 and the understanding that the space weather circumstances will happen again (https://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm)

and with much more dire outcomes due to our technologically-dependent space-faring lifestyle reveal two needs: 1) to understand and develop capabilities to predict space weather and 2) to better integrate information from across domains like the Earth and Space Sciences and the cutting-edge approaches to do so.

The National Science Foundation Convergence Accelerator Convergence Hub for the Exploration of Space Science (CHESS) project is a response to both.

WHAT IS THE CHALLENGE?

Three barriers hold back the development of a comprehensive space weather understanding:

1. The lack of a cohesive community, owing to the wide variety of subject matter experts required;
2. The lack of effective data sharing, coordination, and analysis (e.g., data science) to leverage existing resources and knowledge efficiently; and
3. The diversity of physically dominant processes in across the solar terrestrial connection, making it difficult to relate various models and observations.

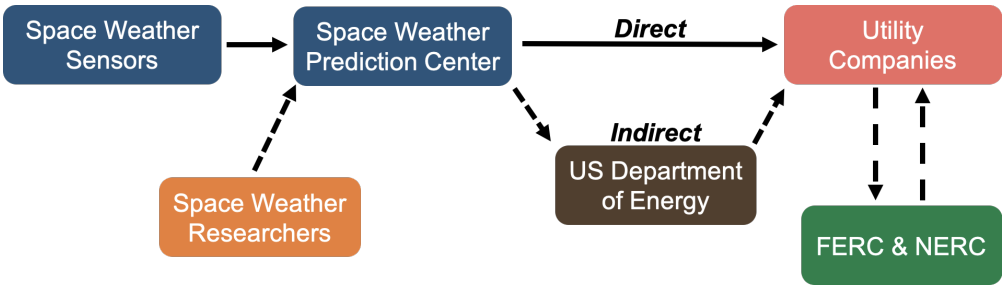
The Convergence Hub for the Exploration of Space Sciences (CHESS) (https://www.nsf.gov/od/oia/convergence-accelerator/Award%20Listings/Track%20A%20Abstracts/A-7152-McGranaghan-ASTRA.pdf)is an NSF-funded project in the Convergence Accelerator Program (https://www.nsf.gov/od/oia/convergence-accelerator/) that is addressing the root cause of these barriers, namely that large volumes of data can often be found in communities that are disconnected from each other, yet study the effects of essentially the same phenomena. We focus on one of the most severe areas threatened and impacted by space weather - the electric power grid.

The electric power grid is perhaps the most critical system affected by space weather, yet ironically may be the least well-specified. During periods of enhanced space weather activity, a series of physical processes beginning with the launch of a coronal mass ejection (CME) or a high speed stream (HSS) from the Sun gives rise to intense electric currents reaching millions of Amperes surrounding the Earth, which then become electric currents on the ground flowing through electrical transmission lines. This phenomenon, known as Geomagnetically Induced Currents (GICs), can disrupt the operation of high-voltage power grid transformers via overheating and generation of harmonics, potentially leading to failures. The March 1989 geomagnetic storm mentioned is an example, but we know that more severe solar events have occurred (see 1859 Carrington Event (https://www.history.com/news/a-perfect-solar-superstorm-the-1859-carrington-event)) and will happen again.

CHESS is the novel solution that is eliminating these barriers through convergence and an open knowledge network (OKN) (https://www.nitrd.gov/news/Open-Knowledge-Network-Workshop-Report-2018.aspx).

WHAT IS THE OPEN KNOWLEDGE NETWORK APPROACH?

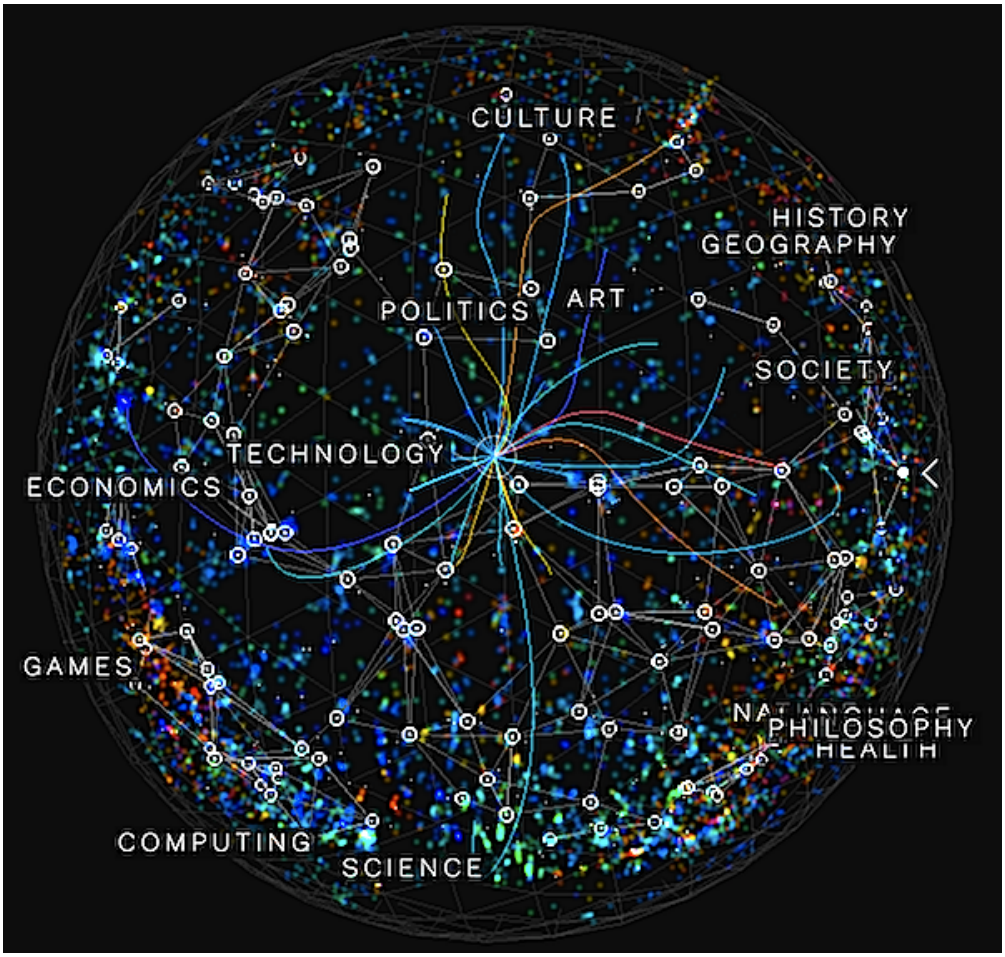
The Convergence Hub for the Exploration of Space Sciences (CHESS) is attempting to create a cohesive, inclusive, cross-cutting, digitally-empowered community for a flourishing electric power grid by developing next-generation data technologies that can be used by each layer in the **Geomagnetic Disturbance (GMD) Information Flow Pipeline** (shown below) for space weather impact on the power grid.



Our solution is to build an **Open Knowledge Network (OKN) (https://www.nitrd.gov/news/Open-Knowledge-Network-Workshop-Report-2018.aspx)** that semantically links concepts and data that span the relevant disciplines of space weather and the areas that are impacted.

Knowledge networks are systems that explicitly link entities (these could be individuals, data sets, disciplines)

Wikipedia is a powerful example: a 3D visualization of Wikipedia (https://www.wikiverse.io/). How does Wikipedia structures data? Through a knowledge network - DBPedia (https://wiki.dbpedia.org/).

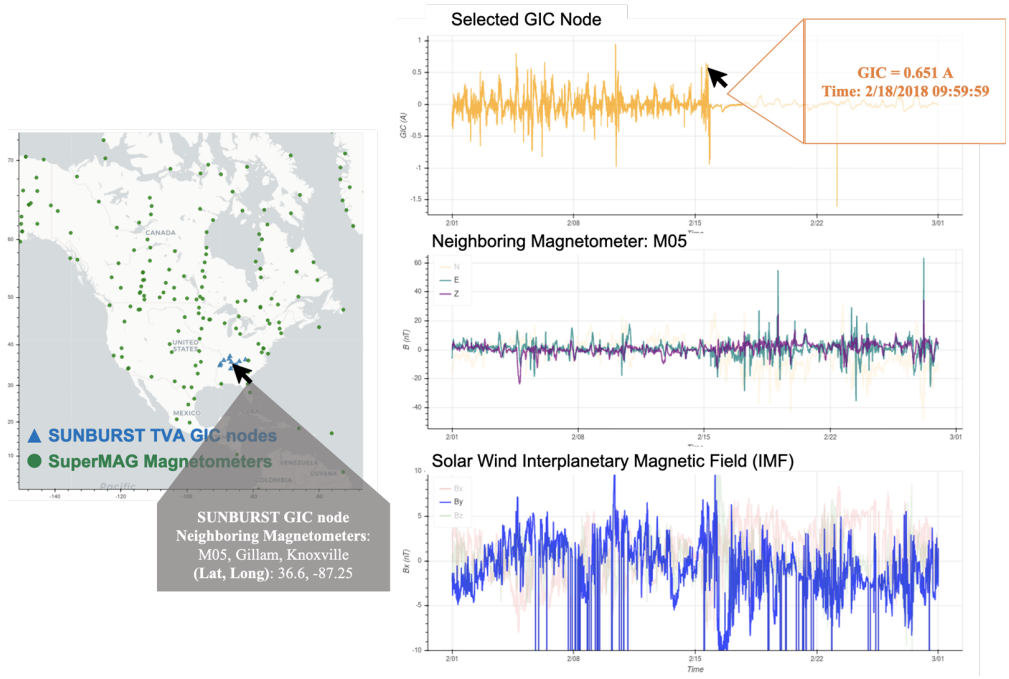


The key challenge in constructing an OKN is to determine how to semantically structure information so that it is interoperable (simply put: using the same terminology and mapping between terminologies). The CHESS project is developing this semantic structuring for the sun-to-power grid application.

Our OKN provides resources to each component in the GMD Information Flow Pipeline, allowing the relevant data, previously dispersed and disconnected, to be readily searched and used (we define *usable* as accessible, labeled structured, and organized).

We have developed a prototype of this OKN, which includes three layers:

1. Information layer: Semantically-linked multi-domain data forming a vast and complex network of knowledge;
2. Analysis and Application Layer: The machine engine for interactive data exploration (at regional and local levels), application of GIC models, and interoperable with other software. The dashboard overlaying the first two layers is shown below); and
3. Communication Layer: A decision support system that connects each user to the right level of information.


Selected GIC Node
GIC = 0.651 A
Time: 2/18/2018 09:59:59
Neighboring Magnetometer: M05
Solar Wind Interplanetary Magnetic Field (IMF)
SUNBURST TVA GIC nodes
SuperMAG Magnetometers
SUNBURST GIC node
Neighboring Magnetometers:
M05, Gillam, Knoxville
(Lat, Long): 36.6, -87.25

WHAT IS POSSIBLE?

We demonstrate the potential of the CHESS OKN in two applications:

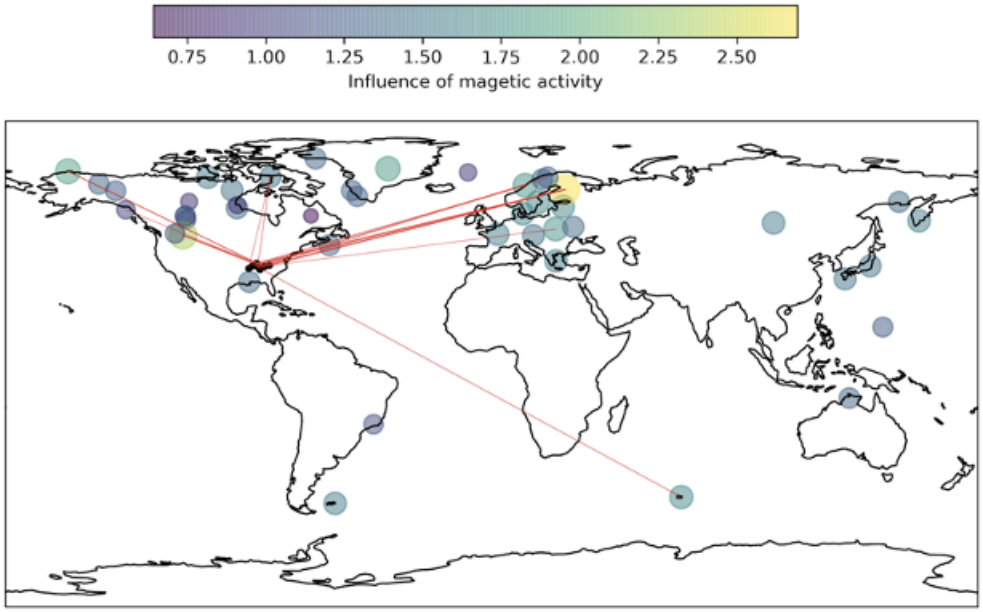
1. Investigation of spatiotemporal connections between ground-based magnetometers and geomagnetically induced currents (GICs) via network analysis; and
2. Exploration of machine learning modeling to predict GICs.

Both applications are made possible by the new and more capable integration of information via the CHESS OKN.

1. Network analysis

Using six months (January-June 2018) of Super Magnetometer Initiative (SuperMAG (http://supermag.jhuapl.edu/)) ground-based magnetometer data linked to newly available GIC data from the Electric Power Research Institute (EPRI) Sunburst Project we construct dynamical networks based on connections between significant responses in magnetometer and GIC data.

From these networks we can study the relationships between magnetic activity (as measured by the magnetometers) and impact on the power grid (as measured by the GICs). Below we show one such result which reveals for a small subset of the GIC data from the Tennessee Valley Authority (TVA) which magnetometer locations exert the most influence.

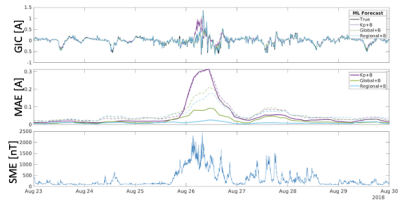


The size and color of the SuperMAG sites indicates the mean influence that each magnetometer has on the TVA sites. The 20 strongest influences are shown as red lines connecting the TVA sites to the SuperMAG sites.

2. Machine learning

We have developed several prototype machine learning (ML) GIC prediction models. The models displayed here employed a deep neural network comprising one-dimensional convolutional layers, trained on the same data used for the network analysis above, but also including important input information from the solar wind.

The figure below illustrates short-term (5- and 20-minute) model forecasts during the following month, when the largest geomagnetic storm of the year occurred, as illustrated by the bottom panel which shows the SuperMAG AE index. The colors from purple to blue represent an increase in model complexity, achieved by integrating additional space-weather information. Our models begin with the Kp index (purple), paired with a local estimate of the magnetic field perturbations, and advance to ingest solar wind and global-scale indices (green), and finally, multi-scale solar wind, global, and regional information (blue). The latter model best captures the diversity of physically dominant processes connected with the GIC response. It is clear from the mean-absolute error (middle panel) that the multi-scale regional forecast performs best for both the 5-minute (solid) and 20-minute (dashed) forecasts. This example demonstrates the importance of connecting space-weather information with power-grid observations to provide advanced warning of GICs.



Looking forward

CHESS produces new data and their relationships and tools to explore them for the space weather community and a new dashboard product to aid power grid utilities (e.g., power engineers).

CHESS is a foundation for the growth of a space weather OKN in which new data providers such as the NSF-funded Super Dual Auroral Radar Network (SuperDARN) and communities such as the Global Navigation Satellite Systems (GNSS) and the oil/gas industry can join and become a new node in the network.

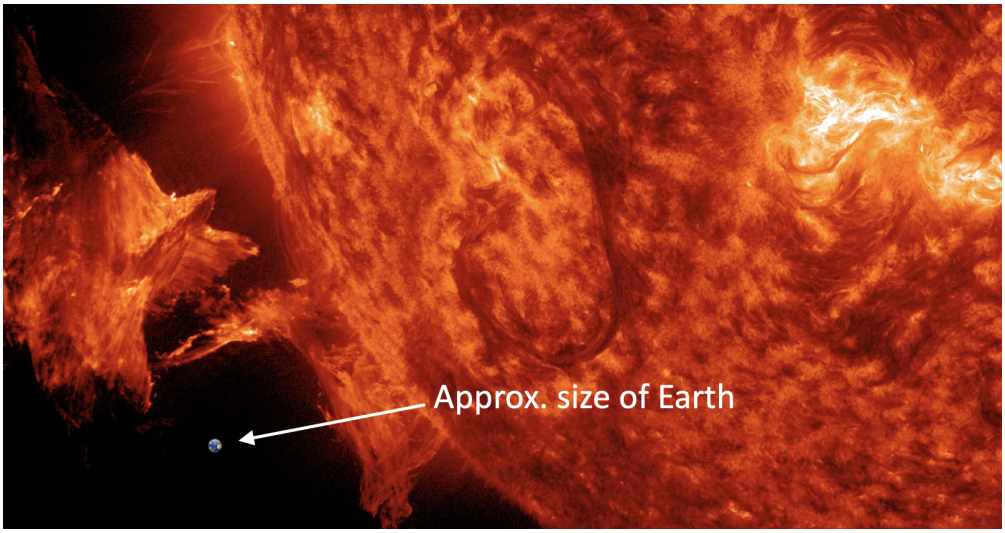
This will require linking to efforts in Heliophysics to develop semantic structures for data, such as the Space Physics Archive Search and Extract (SPASE) (http://spase-group.org/).

HOW DO WE STUDY THE WEATHER IN SPACE?

The fact of the matter is that the vastness of space is *not empty* - it's actually a place with weather and this weather comes from the fact that we live with a star...the sun.

The sun creates everything we need to sustain life, and our living arrangement produces some of the most stunningly beautiful displays in the solar system.

But it's not all good and the weather the sun creates threatens our technologically dependent, space-faring lifestyles.

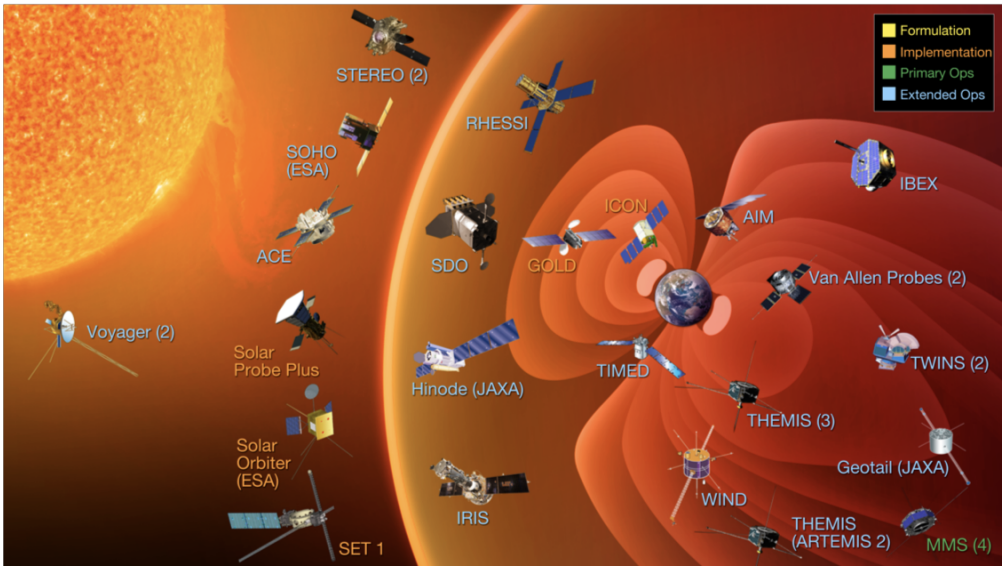


Enormous eruptions from the sun's surface (e.g., solar flares and coronal mass ejections (CMEs)) send radiation and magnetic shock waves into interplanetary space and, if Earth is in the way, a spectacular clash of forces occurs, sending energy into the near-Earth space environment.

The energy dumped into our atmosphere posess a very real very pressing threat to our technologies, systems, and space-faring ambitions. Much like terrestrial weather, there is always weather in space and we are each constantly feeling the impactts as a planet and in different ways depending on where we are.

Space weather requires information from across the Sun-to-Earth connection, making integration of information and disciplines imperative.

We now have instruments on Earth and in space that study every part of our interaction with the Sun 24/7 - *the Space Weather Observational Fleet*.

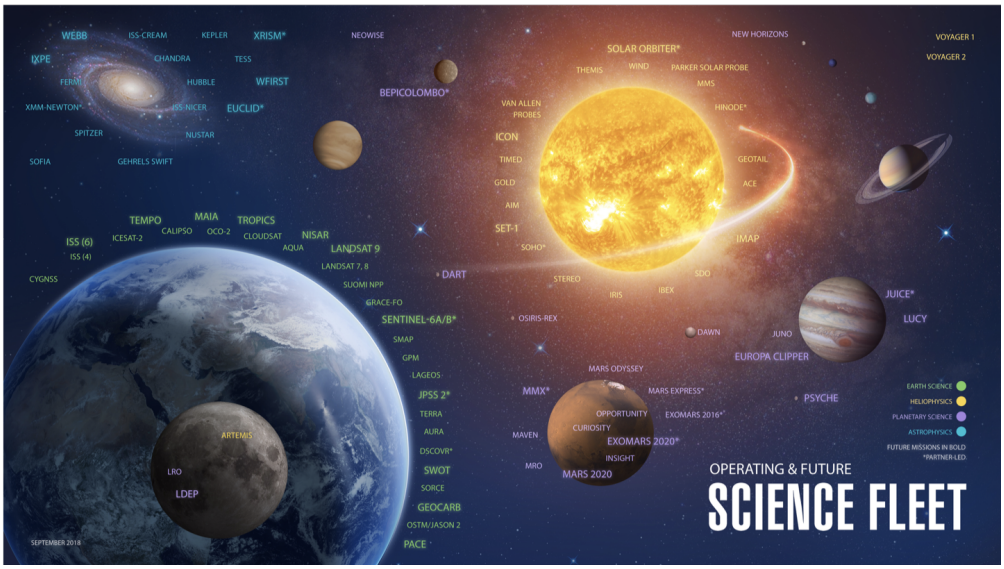


To utilize the observational fleet we must integrate data across the solar-terrestrial system: including from the sun, solar wind, and geospace (the magnetosphere, the Earth's upper atmosphere, and ground-based data that sense phenomena in the Earth's space environment or tangible effects on the Earth).

WHAT DOES THIS MEAN ACROSS THE EARTH AND SPACE SCIENCES?

The OKN approach has the potential to converge the Earth and Space Sciences by linking to similar efforts. The convergent community can grow like the world wide web.

We welcome ideas for linking projects across the EarthCube community and 'moonshot (https://x.company/)' thinking to converge the Heliophysics, Earth Science, Planetary Science, and Astrophysics!



Reach out to link efforts!

Twitter: @AeroSciengineer (https://twitter.com/AeroSciengineer)

Email: rmcgranaghan@astraspace.net

Find a curated set of data science tools and resources (https://github.com/rmcgranaghan/data_science_tools_and_resources/wiki/Links)

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