Title of the white paper: The Atmospheric eXploration and Investigative Synergy (AXIS) Group: proposal for a new interdisciplinary NASA Assessment/Analysis Group (AG)

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The Atmospheric eXploration and Investigative Synergy (AXIS) Group: proposal for a new interdisciplinary NASA Assessment/Analysis Group (AG). K. McGouldrick, et al.

N.B., Parts of this White Paper are reproduced from a Nature Geosciences Commentary article written by the Primary Author [7].

Executive Summary: The study of planetary atmospheres in a truly comparative manner will require a devotion of resources and a philosophy of planetary exploration that differs from the current trend. Fly-by, Orbit, Land, Sample Return does not easily mesh with a requirement for global, long-term monitoring of an atmosphere to characterize the spectrum of spatiotemporal changes that define it. Such investigations of atmospheres within NASA's Planetary Science purview will be essential for maximizing the understanding of information returned from the characterization of terrestrial exoplanets under the purview of NASA Astrophysics. The heritage of models to elucidate the required atmospheric observations draws heavily upon those already utilized in the purview of NASA Earth Sciences, and will enrich such efforts. Finally, the commissioning of multiple spacecraft, all focused on characterizing the range of drivers of planetary atmospheric evolution – the largest of which invariably is the Sun – will lead to improved understanding of the Heliospheric environment (obviously under NASA's Heliophysics purview). Hence, the establishment of an organization whose purpose is to foster such exploration of planetary atmospheres will have broad ramifications both for planetary science, as well as cross-disciplinary benefits across all four of NASA's science subdivisions.

There is much we do not understand about Earth's atmosphere or those of other planets. Was Mars once warm and wet? How did Venus lose its water? Why does Titan have an atmosphere? How will human activity affect Earth's future climate? Which exoplanets are potentially habitable? Each of these questions points back to the same simple, fundamental question: How do planetary atmospheres evolve? Answering this question is vital to understanding not only Earth's atmosphere in the face of climate change, but also the expanding exoplanetary zoo of planets identified orbiting other stars.[1] **We call for a substantial increase in efforts to characterize and understand the diversity of atmospheres in our Solar System through the establishment of an inter- and cross-disciplinary analysis and advisory group, called the Atmospheric eXploration and Investigatory Synergy (AXIS) Group.** This group's purpose would be twofold. First, it would curate a database of atmospheric data, including both observational data and derived data in the form of retrieved atmospheric parameters, as well as atmospheric model inputs and outputs. Second, it will serve as a sort of "Town Hall" for comparative planetology research, discussion, and planning of mission and exploration roadmaps. Such investigations will serve to benefit not only planetary science, but also exoplanetary astronomy, and Earth atmospheric science. Furthermore, the AXIS Group can serve as a model for future similar process-focused (rather than target-focused) assessment/analysis groups.

Over the past twenty years, high precision velocimetry and photometry have enabled

[1] https://exoplanetarchive.ipac.caltech.edu/

the detection and characterization of planets orbiting other stars. As a consequence, our knowledge of the number and variety of planets in the universe has compounded dramatically. However, the limitations of the currently available exoplanetary data have led to significant disagreements within the community with regard to how similar any of these planets might be to Earth, and whether they might support water or even life [11, 2, 10]. Similarly, the divergent atmospheric evolution of Solar System worlds remains poorly understood. We argue that comprehensive observational campaigns of terrestrial planetary atmospheres, and subsequent validation of sophisticated atmospheric models using such data, and testing of scientific hypotheses, are our best bet to understand the divergence of atmospheric evolution seen in our own solar system and beyond.

Until very recently, only the distance, insolation, mass, and radius of a terrestrial-sized exoplanet, depending upon the observational conditions, could be measured. Based on this limited information alone, one would predict that Mars has been tens of degrees below the freezing point of water throughout its entire existence, and that both Earth (almost but not quite too cold) and Venus (almost but not quite too hot) are just barely capable of supporting life. However, factor in the radiative effects of their atmospheres, and the surface of Earth becomes habitable, Mars can potentially support life, and the surface of Venus becomes an oven. The atmosphere of a terrestrial planet can have a substantial influence on the planet's habitability.

Terrestrial-sized exoplanets are nearly impossible to distinguish from their much larger and brighter parent stars. However, when a planet passes directly in front of its star, telescope observations of the transmissivity of its atmosphere tell us a great deal about the bulk atmospheric composition, at least of the upper atmosphere. Although clouds complicate observations of the deep atmosphere, early studies of Venus demonstrated that the likelihood of habitability can be reasonably assessed even when the surface cannot be sensed: CO_2 observed above the clouds implied high surface temperatures that would make the surface of Venus uninhabitable by known life on Earth [1, 13].

However, planetary atmospheres are dynamic in both space and time. As we know from Earth, estimates of simple bulk properties are insufficient to constrain atmospheric evolution. The terrestrial planetary bodies of our solar system provide us with a variety of planetary evolution scenarios. To understand how these – and exoplanetary – atmospheres came to be, we must work backwards from their present compositions and properties.

Planetary Science – especially when applied to terrestrial-scale planets such as Venus, Mars, and Titan – is essentially the application of Earth Science to extraterrestrial worlds. Over recent years, the recognition of the inherent comparative nature of such an endeavour has been more thoroughly explored by the Planetary Science community. A primary goal of the "Exploring Venus as a Terrestrial Planet" Chapman Conference in 2006 was to "review current knowledge of Venus and compare [it] with Earth and Mars," the organizing committee having recognized the key role that the study of Venus could play in understanding Earth in particular and terrestrial planets in general. This meeting subsequently led to an ongoing series of conferences held in Boulder, CO (2012), Mountain View, CA (2015), and Houston, TX (2018), entitled, "Comparative Climatology of Terrestrial Planets," in which the concept of comparative planetology was progressively more thoroughly explored in the context of comparisons within our solar system. The recognition of the role of comparisons with terrestrial exoplanets grew with each iteration of that meeting, as is perhaps most evident from the related "Exoplanets in Our Backyard" conference held in Houston, TX in early 2020, co-sponsored by the Venus Exploration and Analysis Group (VEXAG), the Outer Planets Analysis Group (OPAG), and the Exoplanets Analysis Group (ExoPAG). The last decade and a half have demonstrated a steady development of the concept of comparative planetology from an isolated exercise in primarily venusian studies to one that contemplates worlds throughout the galaxy. Here, we propose taking the next natural step in this process by laying the foundations for an effort to explore all terrestrial planets, literally, as Earthlike worlds. Specifically, we propose applying the lessons learned from the study of the Earth system by NASA's Earth Science Division to the study of terrestrial planets throughout our solar system and the galaxy.

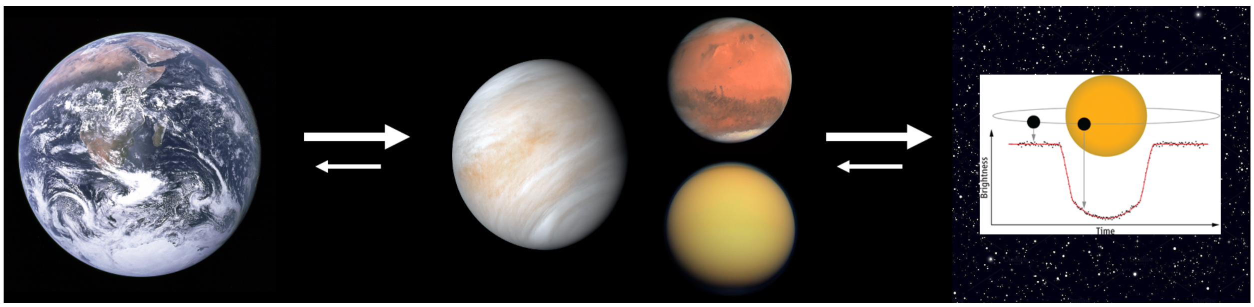

Figure 1: The flow of information that results from coordinated study of the Earth, Solar System planets, and Exoplanets.

The overarching science questions applied to Earth in the NASA Earth Strategic Plan apply equally well to any atmosphere-bearing planet in the solar system. Below we list the key science questions to be answered through the NASA Earth Science Program, according to the 2014 NASA Science Plan [8][2], noting that replacing "Earth" with "planetary" in each of these, equally viable and interesting science questions are formed that have direct impact on the study of targets of NASA's Planetary Division: Venus, Mars, and Titan, as well as on exoplanets, a target class within NASA's Astrophysics Division:

- How is the global [Earth, planetary] system changing?
- What causes these changes in the [Earth, planetary] system?
- How will the [Earth, planetary] system change in the future?
- How can [Earth, planetary] system science provide societal benefit?

A planetary atmosphere is a four-dimensional heat engine that exhibits variability over a wide range of both spatial and temporal scales. In order to understand the nature of all of the interconnected processes at work, it is vital both to acquire observational data that can be analyzed to detect changes over such a wide range of spatiotemporal scales, and to develop models capable of testing these processes at the spatiotemporal resolutions on which they occur. Such comparative climatology permits the observation of similar physical phenomena acting over a wide range of typical conditions and forcings; as well as providing

[2]Retrieved from `https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2014_Science_Plan_PDF_Update_508_TAGGED_1.pdf`

a testbed whereby models can be pushed beyond their parameterized comfort zones in order to distinguish between those physical processes which are truly understood and those which are merely reproduced.

This effort is analogous to the key role that the generation of geological maps plays in helping to decipher the information embedded within the observational data of the surface of a planet. Being able to identify characteristic features and regions and units, how they are emplaced, and how they may have interacted during their histories helps to characterize the evolution of a planetary surface much more comprehensively than the raw imagery themselves can. For planetary atmospheres, the transport and evolution of key species over time similarly tells a rich story of planetary evolution that monochromatic images or individual spectra cannot. However, the data from a terrestrial planetary atmosphere exhibits scientifically relevant information in two additional dimensions that a planetary surface does not: altitude and time. Furthermore, because a terrestrial planetary atmosphere exhibits temporal variability on timescales orders of magnitude shorter than a terrestrial planetary surface – as brief as minutes to hours, as compared with millions to billions of years – the time dimension is of vital necessity in making sense of such data in a way that it is not for geological mapping purposes.

In order to accomplish this for a given terrestrial atmosphere, it is necessary to obtain, at spatiotemporal resolutions that are suitable for data assimilation into current models of planetary atmospheres (from global scale to regional scale) observational measurements of three dimensional wind vectors (u, v, w), atmospheric structure (Temperature, Pressure, density, and composition), as well as energy sources (*e.g.,* insolation, greenhouse warming, and even internal heat release), in four spatiotemporal dimensions (longitude, latitude, altitude, time). The spatial resolutions required will differ (both in time and space) whether the scientific question pertains to a global (*e.g.,* Hadley Circulation, the Retrograde Zonal Super-rotations of Venus and Titan, Martian Global Dust Storms), regional (*e.g.,* Venus North and South Polar Vortices, Titan's climatological hydrological cycle, Martian regional dust storms, and impact events), or mesoscale (*e.g.,* dust devils on Mars, dunes on Mars, Titan, and Venus, and gravity waves on Mars and Venus) process. The temporal resolution required is driven by the need to be able to distinguish between "weather" and "climate" (depending largely upon the time persistence of each phenomenon).

On Earth, about ten thousand ground stations scattered across the globe are recording meteorological measurements with at least hourly frequency[3]. From about three hundred of these stations, two vertical soundings per day are also obtained by weather balloons. In addition, a fleet of about thirty satellites in low-Earth-orbit monitor aerosol concentration, CO_2 abundance, surface albedo, temperature, and many other parameters. Several of these are obtained contemporaneously by a constellation of satellites called the "A-train," each member of which passes over nearly the exact same afternoon track on the planet to within about 15 minutes [6]. Finally, about a half dozen geostationary satellites orbit high above the equator, observing global circulation and providing a global context for the higher precision localized measurements of the A-train [9].

Thanks to this ongoing monitoring effort, coupled with an equally intensive atmospheric modelling effort [4], we have come to understand the workings of the current Earth's atmo-

[3]NCAR Real Time Weather Data Page (`http://www.rap.ucar.edu/weather/surface/stations.txt`)

sphere to astounding precision and accuracy. Yet, many uncertainties remain, particularly with how all this data is used to parameterize and validate General Circulation Models. Such models, if they are tuned too finely to the current data for which they are calibrated, can lose fidelity when applied to an atmosphere significantly different from the modern Earth situation, whether an early or future Earth atmosphere or another planetary atmosphere. The inclusion of observational data from different atmospheres produces greater confidence in the prognostic models. But because it is thought to be prohibitively expensive, we have not monitored other planetary atmospheres to the extent we do for Earth.

We propose the establishment of a new interdisciplinary and cross-disciplinary process-driven advisory/ informational group focused on the assessment of the state of the comparative study of terrestrial planetary systems, from Earth, to the solar system, and to exoplanets. The goals of the AXIS Group would be patterned after NASA's successful Earth Science Division program for studying a planet as a system of many interconnected processes. Recognizing that "Our planet is changing on all spatial and temporal scales and studying **Earth as a complex system** is essential to understanding the causes and consequences of climate change and other global environmental concerns," the primary mission of NASA's Current Strategic Plan for Earth science "is to advance our scientific understanding of **Earth as a system** and its response to natural and human-induced changes and to improve our ability to predict climate, weather, and natural hazards."[8]

The challenges being overcome in the most recent Earth Science NASA Strategic plan will apply to the study of **planetary systems in our solar system and beyond**. Namely, the dramatic rise in data volume that will require improvements in storage and processing capability, as well as incorporation into analysis of such data through models of planetary systems, usually via supercomputing facilities. The implementation of the modelling efforts for Earth science apply equally to planetary science:

- Model predictions are compared with observations as a means of determining the extent to which we understand the physical processes driving the [Earth, planetary] system.
- Model predictions are integrated with observations to provide a best estimate of the current state of many [Earth, planetary] system components using a method called data assimilation.
- Models are used to provide short term forecasts the support field missions and longer term forecasts to assess potential responses of the [Earth, planetary] system to various drivers of change.

In each of these, as before, "Earth" can be replaced by "planetary" and the meaning and need for such efforts is consistent. In fact, multiple White Papers will have been submitted that call for a scientific focus on these very questions as they pertain to Mars (by first authors Diniega, Guzewich, and Newman), Titan (by first authors MacKenzie, and Nixon), Venus (by first authors Brecht, and Royer), and Exoplanets (by first authors Crichton, and Fortney). Due to the lack of current human activity beyond Earth orbit, the connection present in the third of these is perhaps less obvious; but one could imagine the need for future short-term forecasts of surface conditions on a body such as Mars, if we are to consider semi-permanent human exploration of such planets in the not too distant future. In addition to all of this, Comparative Planetary Atmospheric Science further brings to the table the ability (even a requirement) to push our existing models to their limits by using them to analyze and predict a wide variety of conditions, not only on a planet-by-planet basis, but also of individual planets over geological time scales.

We further propose the establishment of a system for archiving observational data, modelling outputs, and models themselves for use in the assessment of Venus, Mars, Titan, and exoplanets as planetary systems, and to facilitate the intercomparisons of both the targets (planets) and tools (models) of these efforts. The Earth Science Division has already shown how to tackle this problem through the establishment of EOSDIS (Earth Observing System Data and Information System) which curates and distributes an observational data volume that exceeds 5 Tb/day; and through the NASA Earth Exchange (NEX), which provides "a mechanism for scientific collaboration and knowledge sharing" through the application of Earth system modelling via supercomputing facilities, and remote sensing data. We propose a similar system for interplanetary comparisons. As this is more than just a data and tool exchange, having a larger science component that derives from the application of common models across disparate planets, or application of several models to a single planet, we propose that the analogous group for NASA planetary sciences take the form instead of an Assessment or Advisory Group in which it is recognized not just as a tool (like PDS), but also as a forum for bringing together "like minded" scientists and engineers for collaborations that can more effectively move forward the field of comparative planetary system science. We anticipate that the AXIS Group concept can be extended to other planetary processes (*e.g.,* geophysics and space physics), building upon the multi-AG, interdisciplinary work that the recent "Exoplanets in Our Back Yard" meeting showed to be possible.

The primary requirements for AXIS would be (mirroring in many ways, the aforementioned and described EOSDIS):

- Develop and maintain a centralized data archive for derived atmospheric quantities from all terrestrial planets, in four dimensions.
- Recognizing the preponderance of use of NetCDF data – which are de facto not PDS-compliant – in atmospheric modelling work across planetary and Earth science disciplines, A PDS archive of these data would require both the servers capable of storing the data in compliant and non-compliant formats, as well as maintenance of simple-to-use tools for converting these data to NetCDF formats in a consistent manner.
- Advocate for funding mechanisms to support the generation and documentation of atmospheric data products from existing and future spacecraft data.
- Establish a standard set of "validation simulations" against which existing and future atmospheric models (and their future updated versions) may be evaluated and compared.
- Advocate for funding mechanisms to support the inter-comparison of models (similar to that performed in the course of an International Space Science Institute (ISSI) workshop by the Venus community a decade or so ago [5], and which already exists in Earth Science (Coupled Model Intercomparison Project (CMIP)).
- Develop and maintain an archive of model initialization data at common resolutions and formats, to facilitate replication of theoretical works and further enhance interplanetary and inter-model comparisons.

- Help maintain NASA's GitHUB for atmospheric models and advocate for common model documentation standards and common model output format standards.

In a practical sense, this would require the establishment of an additional node of NASA's Planetary Data System. At the moment the Atmospheres node is best placed to take on this work, but with even the relatively small amount in planetary atmospheric data obtained so far, and given the determination that data formats common in the atmospheric modelling community (*e.g.,* NetCDF) are not compliant with PDS standards of a long-term archive, it is unlikely that PDS Atmospheres, without a significant increase in NASA support would be able to take on such a burden. Instead, a separate and distinct node that is capable of bridging the gap between Earth science and planetary scienceand is prepared to take on the burden of the archiving of models is required [12].

Four hundred years ago, the invention and utilization of the telescope instantly increased by an order of magnitude the number of worlds we could study. Today, the identification of what are probably trillions of planets in our galaxy alone [3] is providing thousands of targets for further investigation. Just as the telescope introduced and required new techniques and mindsets in order to fully grasp the planets that had become within focus, so too does the burgeoning field of exoplanetology.

We cannot hope to decipher exoplanetary atmospheres without understanding the atmospheres closer to home. It is time we took the next step and built the AXIS that will connect the multiple planetary wheels on which the wagon of scientific progress in planetary atmospheric science might advance.

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