# Solar System Science in the Next Decade

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# Why Study the Solar System?

- Explore our surroundings

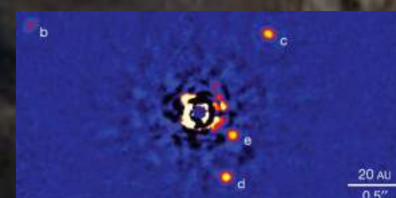





- Understand our origins

- Use to understand nature and potential origin of other systems (and possibly life!) elsewhere

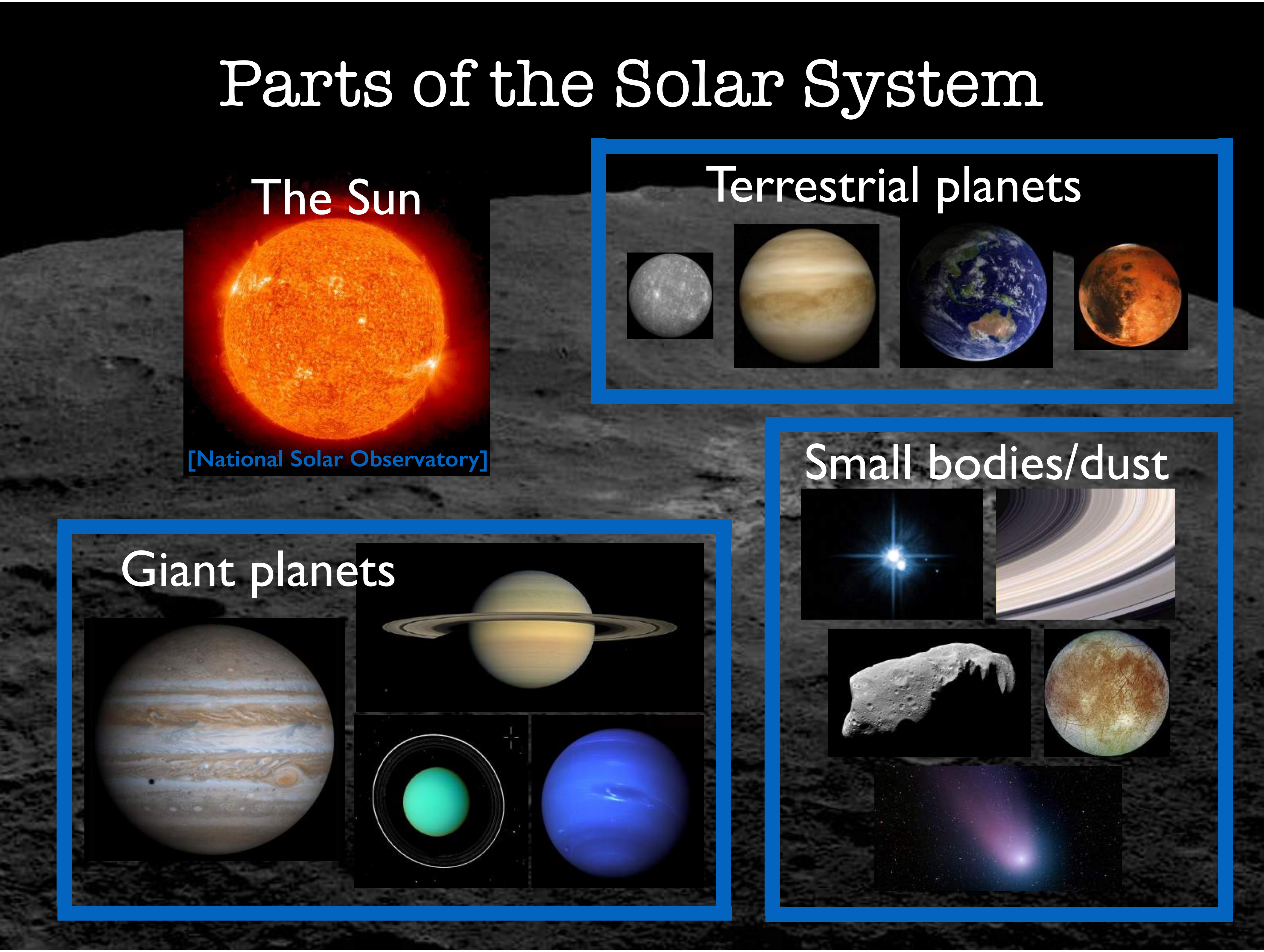





- Understand and attempt to mitigate potential hazards






Parts of the Solar System
The Sun
[National Solar Observatory]
Terrestrial planets
Giant planets
Small bodies/dust

# The Terrestrial Planets and the Moon

- Studying climate and geology of terrestrial planets can inform our understanding of conditions necessary for (sustained) life on rocky planets
- Atmospheric, geological, and compositional mapping studies can help pave way for future robotic and human missions
- Detailed observational and in situ studies of terrestrial planets in our own solar system can give context to and aid interpretation of exoplanet observations

# The Terrestrial Planets and the Moon

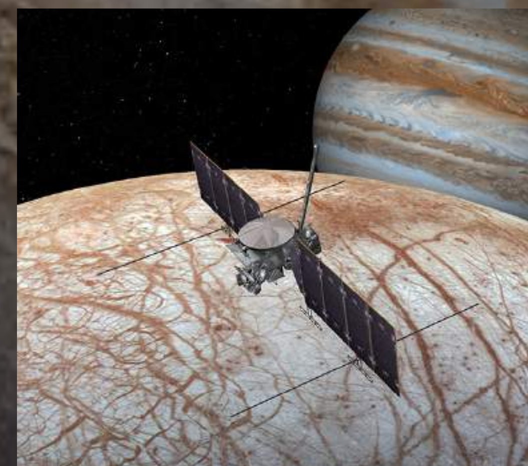
- NASA-related priorities identified by LEAG (Moon), VEXAG (Venus), and MEPAG (Mars) advisory groups
- The Moon
  - Study scientific and resource implications of polar volatile deposits; understand past/present geological processes; plan for human exploration to and beyond the Moon; develop public-private partnerships for planetary exploration
- Venus
  - Understand atmospheric formation, evolution, and climate history, evolution of the surface and interior, and the nature of interior-surface-atmosphere interactions over time
- Mars
  - Determine if Mars ever supported life, understand the processes and history of climate, understand origin and evolution as a geological system, and prepare for human exploration
  - Mars 2020 rover: search for signs of past habitable conditions and ancient microbial life itself, collect samples for future return, and test technologies for future human exploration
- Most high-priority objectives involve spacecraft missions

# Giant Planets and Their Satellites

- Detailed ground-based and spacecraft-based studies of atmospheres, seasonal changes, magnetospheres, and interiors of giant planets provide insights into the formation of our own solar system and planet formation in general
- Multiple giant planet satellites suspected of having subsurface oceans and potentially even life (e.g., Europa, Enceladus, Titan); could be best opportunities for finding present-day extraterrestrial life
- Studies of both giant planets and satellites provide context for understanding and interpreting exoplanet observations

# Giant Planets and Their Satellites

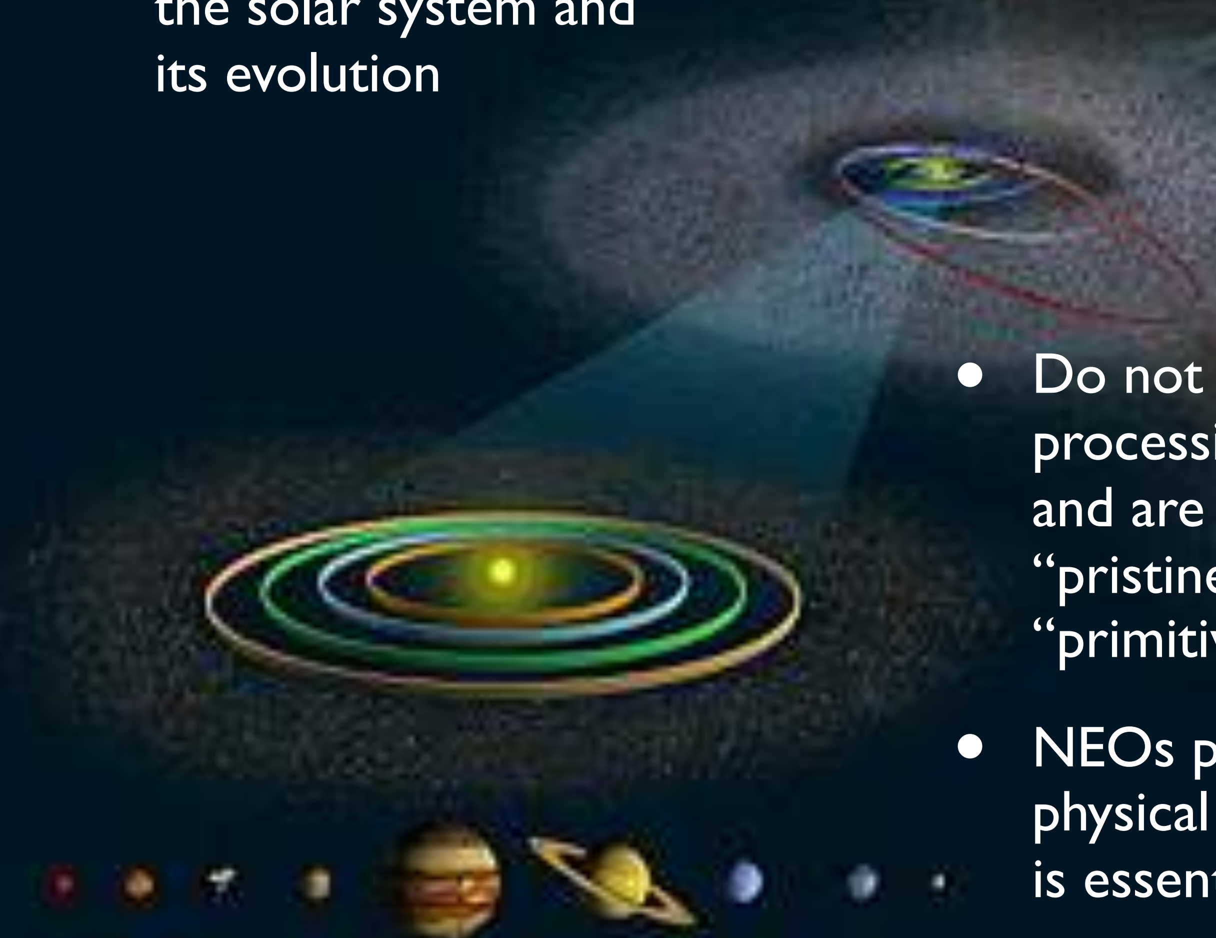
- NASA Outer Planets Assessment Group (OPAG) priorities largely focused on spacecraft



- Europa Clipper (expected launch in early 2020s) is high priority as well as proposed Ice Giant Systems mission to Neptune or Uranus; future (lander) missions to search for life on Europa or Enceladus also desired
- ESA's JUpiter ICy moons Explorer (JUICE; expected arrival in 2029) will study Jupiter, Ganymede, Callisto, and Europa
- Dragonfly (Titan lander) selected for New Frontiers Phase A concept study

# Small Solar System Bodies

- Thought to be leftover building blocks from planet formation
- Can be used as tracers of temperature, composition, and dynamics of the solar system and its evolution



- Do not undergo as much physical processing as planets due to smaller sizes, and are often considered “pristine” (although probably more “primitive” than pristine)
- NEOs present potential hazards where physical and astrometric characterization is essential for mitigation

# Small Solar System Bodies

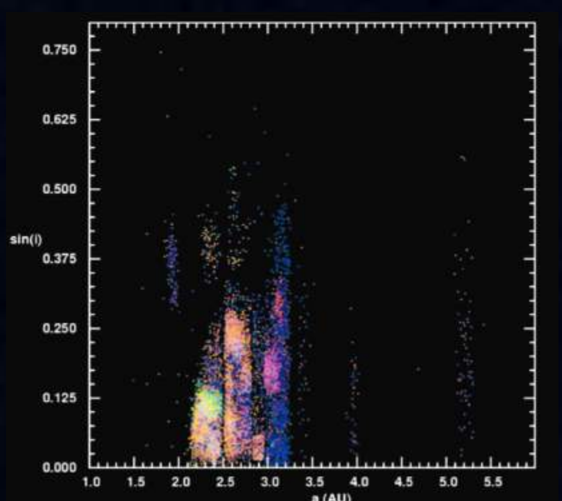
- SSSB science already heavily driven by surveys (Catalina, Pan-STARRS, ZTF, etc.); will be revolutionized by LSST in the next decade
- Tens of millions of observations expected for both known objects and new discoveries; known objects in various SSSB populations expected to increase by an order of magnitude or more
- Advance development of tools for managing large quantities of data, producing higher-level data products, and quickly identifying transient phenomena of interest, as well as robust follow-up capabilities will be crucial for maximizing SSSB science in the LSST era

# Small Solar System Bodies

- **Near-Earth Objects (NEOs)**
  - Present opportunities for studying SSSBs at extremely close proximity; also of interest for in-situ resource utilization (ISRU) and commercial asteroid mining interests


  - Rapid follow-up important for orbit determination, characterization, and hazard evaluation

- **Asteroids**
  - Increased rate of detection of active asteroids by LSST will increase opportunities to study such events in real-time
  - Number of asteroids with known physical properties will increase greatly, enabling improved population-level studies




Ivezić et al. (2002)

- **Trans-Neptunian Objects (TNOs)**
  - Increased population numbers and compositional information will improve understanding of dynamical and compositional structure
  - Increased number of known distant solar system objects will have implications for inferring existence of or directly observing unknown distant planet(s) (i.e., "Planet X")

# Small Solar System Bodies

- Comets
  - Deeper surveys will detect incoming comets at much greater distances, allowing longer-baseline monitoring as they approach the Sun, and also uncover weaker comets, possibly in unexpected places (e.g., asteroid belt, Jovian Trojans, etc.)
  - ELTs will enable more detailed compositional studies of broader range of comets
- Interstellar Objects
  - First identified ISO discovered in Oct 2017 by Pan-STARRS1; was $m_V$~19.7 at discovery, and then $m_V$~23.4 two weeks later
  - ISOs provide actual samples of other planetary systems
  - LSST should find more, but will require extremely rapid follow-up
- Mission support
  - Many missions to SSSBs in coming decade; all will need ground-based reconnaissance to ensure mission success as well as additional observational support to provide context and extend spacecraft findings to broader populations

# Upcoming Solar System Missions

- NASA Discovery-Class Missions
  - Lucy (Trojan multi-flyby mission) and Psyche (mission to study a metallic asteroid) missions set to launch in early 2020s; NEOCAM (infrared survey telescope) also awarded development funding

- NASA Planetary SmallSat Studies (PSDS3)
  - Recent selections include mission concepts to study the internal structure of asteroids, and Phobos and Deimos (also the Moon, Venus, Mars, Jupiter, and Uranus)

- NASA New Frontiers Missions
  - CAESAR (comet sample return mission) selected for concept study (launch in 2020s)

- International Missions
  - ESA (Europe), JAXA (Japan), CNSA (China), ISRO (India) have active space programs
  - Many missions include both technical and scientific participation from the US

- Asteroid Mining Initiatives
  - Planetary Resources and Deep Space Industries among private asteroid mining companies
  - Luxembourg government pledging investments in asteroid mining industry

# Spacecraft-Telescope Synergy

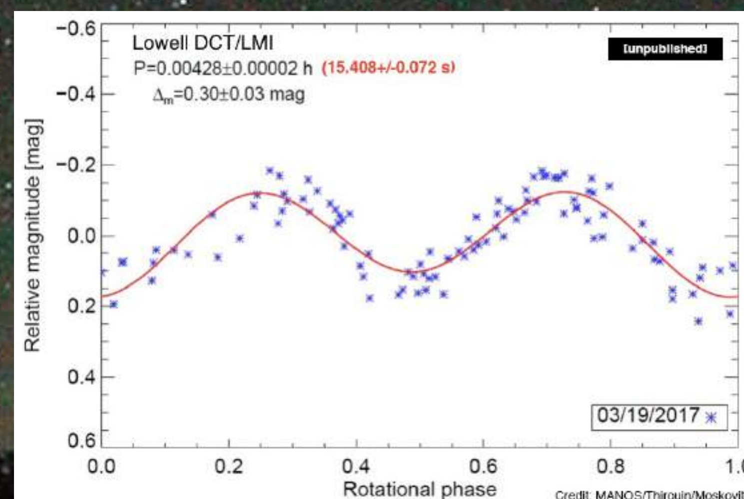
Spacecraft can conduct extraordinarily detailed studies, but ground-based observing support is essential before, during, and after missions

- For major planet/satellite missions, observations are needed to provide global context, proper time coverage/sampling (e.g., in terms of length, frequency, and regularity), and additional wavelength coverage

- For small body missions, observations are needed for target reconnaissance and characterization to ensure mission success, additional wavelength coverage, and to extend the results of spacecraft visits to individual objects to broader populations

# Observational Considerations

- Bright solar system objects are still scientifically compelling, necessitating continued reliable access to small to mid-sized observing facilities in addition to large and extremely large facilities
- Rapid response required for many science cases due to transience of events or limited observing windows
  - e.g., comet outbursts, asteroid disruptions, NEO or interstellar object follow-up
- Versatile observing modes expand range of potential investigations
  - e.g., high-frequency cadences on large telescopes, ability to obtain extremely short observations of bright targets repeated over long periods of time, low-overhead AO, rapid slew/tracking rates, broad wavelength coverage, telescope networks with complete longitude coverage, Gemini-Fast-Turnaround-like programs...



# Conclusions

- Solar system science in 2020s will be heavily driven by spacecraft missions and ground- and space-based surveys
- Spacecraft can conduct extraordinarily detailed studies, but ground-based observing support is essential before, during, and after missions
- Current and upcoming surveys will uncover many more new objects and phenomena requiring follow-up observations than ever before; facilities and mechanisms to enable follow-up on appropriate timescales will be crucial
- Appropriate software tools capable of dealing with large data sets will be essential for taking full advantage of current and upcoming surveys (especially LSST)
- Continued public availability of observing time for PI-led projects on both small and large facilities will be essential for continued innovation and advancement
- Adequate funding of both directly- and indirectly-related scientific activities (e.g., survey science, planetary geology, PI-led instrument development) also needed to take full advantage of operational investments in missions and surveys


Thank you!
Thanks to NOAO for travel support!