CUTTING EDGE PHYSICS IN THE ATOMIC AND MOLECULAR PHYSICS DIVISION, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

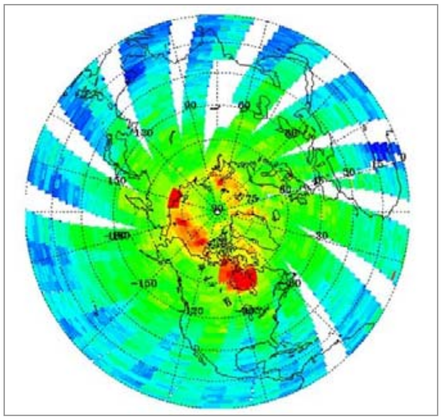
Overview: The Harvard-Smithsonian Center for Astrophysics (CfA) combines the resources and research facilities of the Harvard College Observatory and the Smithsonian Astrophysical Observatory under a single director to pursue studies of those basic physical processes that determine the nature and evolution of the universe. The Smithsonian Astrophysical Observatory (SAO), founded in 1890, is a unit of the Smithsonian Institution. The Harvard College Observatory (HCO), founded in 1839, is a research institution of the Faculty of Arts and Sciences, Harvard University, and provides facilities and substantial other support for the Department of Astronomy. The establishment of the CfA in 1973 formalized the long relationship between the two organizations, which began when the SAO moved its headquarters to Cambridge in 1955.

Today, nearly 300 Smithsonian and Harvard scientists cooperate in broad programs of astrophysical research supported by Federal appropriations and HCO's own endowment, and (mainly) by contracts and grants from government agencies and by contributions from the private sector (individuals, foundations and corporations). These scientific investigations, touching on almost all the major topics in astrophysics, are organized into six divisions. One division, the Atomic and Molecular Physics Division (AMP), focuses on describing and understanding atomic and molecular processes as they relate both to the behavior of objects in the Universe and to searches for new physics.

Atomic and Molecular Astrophysics: The full scientific potential of current and future generations of telescopes, across much of the electromagnetic spectrum from x-rays to radio waves, can be utilized fully only if the fundamental atomic and molecular physics data and their interpretation exist. The research in the AMP division includes theoretical studies and laboratory and field measurements, which support astronomical observations at many wavelengths, address topics of astrophysical importance, and pursue related studies in fundamental physics and atmospheric science. Spin-offs from AMP research include current industrial, medical, communications, and environmental applications.

Studies of the processes of atomic, molecular, and optical physics and chemistry enable research in a number of astrophysics research areas. As examples:

- Modeling of the chemistry of the early Universe clarifies the role molecules may have played in enabling the first generation of stars to form through gravitational collapse.
- Calculations of molecule formation near supernovae and of the chemistry of interstellar clouds may explain a vast range of behavior in the Universe.
- Analysis of spectroscopic observations being made with the instruments on board the Chandra X-ray Observatory enable AMP scientists to study the absorption of x-rays by atomic species. This research helps to explain the measured emissions of X-rays from comets and from the Jovian X-ray auroras over the polar caps.
- AMP laboratory measurements coupled with radio astronomical investigations aim to understand the role of the chemical bond and organic chemistry in nature on a cosmic scale, and to determine the origin of the interstellar diffuse bands, the outstanding unsolved problem in astronomical spectroscopy.



- AMP field measurements programs include satellite-based measurements of the Earth's atmosphere, to study the photochemistry of the stratospheric ozone layer, and the global distributions of atmospheric pollution in the lower atmosphere.

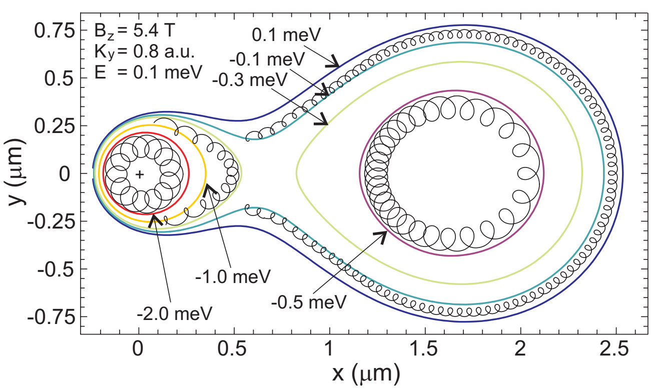
Left: Bromine monoxide over the ice pack in high-latitude springtime. These measurements, made by AMP scientists using data from the European Space Agency's Global Ozone Monitoring Experiment satellite instrument, are used to quantify seasonal destruction of tropospheric ozone.

- Practical applications of theoretical work in AMP include modeling of the emitted light from sodium high-pressure lamps; this has led to measurements in the AMP laboratory used to understanding the characteristics of the atmospheres of brown dwarf stars and gas giant planets.

These investigations and many other similar studies have earned for the CfA a leadership role in atomic and molecular astrophysics.

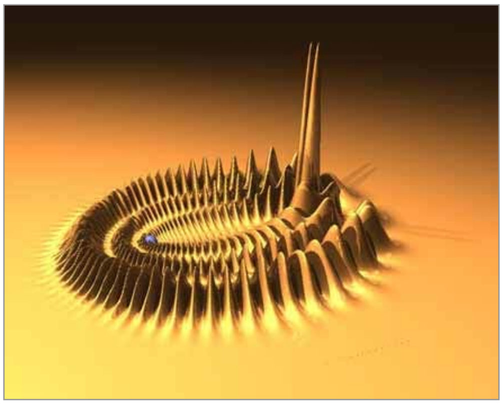
New Physics: SAO is also at the forefront of developing and applying novel technologies to high-sensitivity searches for new physics. This emphasis makes the AMP division unique in its experimental and theoretical strength because it operates at the forefront of atomic and molecular physics while being located at an astrophysics institute. The program attracts leading scientists, who may not have an astrophysics background, to an environment where their skills can be applied both to cutting-edge topics in terrestrial physics as well as to astrophysics. As examples:

- Theoretical studies in fundamental physics include the interactions between matter and anti-matter. Recently, the field ionization and velocity spectra of strongly magnetized antihydrogen atoms were characterized and interpreted in collaboration with the ATRAP experimental group in the Harvard Physics Department.



Left: Radial orbits (black lines) of the positron in an antihydrogen atom crossing a magnetic field. The positron moves in an effective potential (colored lines) from field-induced coupling between internal and center-of-mass motions. Its orbits can be either near the antiproton (left), in an unusual giant dipole basin (inner right), or around both (outer).

- The Institute for Theoretical Atomic, Molecular, and Optical Physics (at the Observatory) is a leading center for research on physics at ultra-cold temperatures (emphasizing Bose-Einstein Condensation).



Right: The existence of a ubiquitous class of ultra-long range molecular Rydberg states was predicted by a JILA/ITAMP collaboration in 2000. These giant molecules have an electron cloud resembling a trilobite, the ancient, hard-shelled creature which existed for 300 million years throughout the Paleozoic era. These molecules, on the other hand, are estimated to live about 1-10 milliseconds!

- Theoretical on nanodevices include proposed nanocentrifuges and stabilizers to damp turbulence in nanosystems.

- AMP research on atomic clocks and quantum optics includes precise tests of fundamental symmetries of physics (Lorentz invariance) which also address questions about the origin and fate of the universe:
    - Measurements on low temperature collisions between hydrogen atoms contribute to the understanding of basic atomic processes.
    - Stored light experiments in quantum optics show that information encoded in a light pulse can be transferred to an atomic system and then retrieved coherently, with potential applications to quantum computing, communications, and cryptography.

- Other applications of AMP measurements include the development and application of new tools for biomedical imaging, like the improved MRI of the lung, and understanding laboratory plasmas, *e.g.*, controlled nuclear fusion.

Right: Graduate student Leo Tsai applying thermally-conductive epoxy to aluminum coil frames in order to mount these on 2-meter diameter solid aluminum flanges. The electrical coils that will generate the applied magnetic field in the second generation human low-field imaging system will then be wound on these supports. The imager will be used in our human orientational lung-imaging project.

Data Archives: The CfA also demonstrates its leadership in the compilation and administration of standard databases. For example, SAO's HITRAN (HIgh-resolution TRANmission molecular absorption database) is used for predicting and simulating transmission and emission of light in atmospheres. It is the world-standard reference database in molecular spectroscopy, with approximately 5000 users worldwide. The journal article describing it is the most cited reference in the geosciences.