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DIVISION D COMMISSION 44

SPACE AND HIGH-ENERGY ASTROPHYSICS

ASTROPHYSIQUE SPATIALE & DES HAUTES ÉNERGIES

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LEGACY REPORT 1994-2015

1. Introduction

Division XI, the predecessor to Division D until 2012, was formed in 1994 at the IAU General Assembly in The Hague by merging Commission 44 Astronomy from Space and Commission 48 High Energy Astrophysics. Historically, space astrophysics started with the high energy wavelengths (far UV, X-ray, and gamma-ray astronomy) which are only accessible from space. However, in modern astronomy, to study high energy astrophysical processes, almost all wavelengths are used (including gamma-ray, X-ray, UV, optical, infrared, submillimeter and radio). In addition other ground-based facilities, including gravitational wave antennas, neutrino detectors and high-energy cosmic ray arrays are joining in this era of multi-messenger astrophysics, as well as space missions with the primary goals to discover and study exoplanets, are under the umbrella of Division XI.

Thus Division XI members represent a very broad community of observers and theorists. Division XI has a single Commission (#44, having the same name as the Division and the same OC as the Division) and two Working Groups ("Astronomy from the Moon", which is an inter-divisional WG together with Divisions XI and X, and "Particle Astrophysics"). Division XI has a total membership of about 1000.

The science areas relevant to Division XI cover almost all astronomical topics, including our Solar System, exoplanets, all manner of stars, plus black holes, the intergalactic medium, individual galaxies and clusters of galaxies, and active galactic nuclei, studies of deep space and cosmology. The breath of our Division implies that communication and cooperation among the Division members, and cross-fertilization with members of other Divisions, are important and helpful to accomplish our scientific goals and to promote new space and ground based observatories.

Figure 1. (left) The Hubble visible light image of the Eagle Nebula shows the three "pillars of creation," structures of cold gas and dust where massive, new stars are forming. (right) The blue haze around the pillers in the Hubble infrared image is material being heated up by the new stars and evaporating into space.

Since its inception on 1994, Division XI has enjoyed very scientifically exciting years. The scientific space missions operating between 1994 and the present that pertain to the Division's scope of interest, in order of launch date, include GRANAT (1989 - 1994) HST (1990 -), ROSAT (1990 - 1999), ASCA (1993 - 2000), Infrared Space Observatory (1995 - 1998), RXTE (1995 - 2012), ACE (1997 -), BeppoSax (1996 - 2003), CHANDRA (1999 -), XMM-Newton (1999 -), FUSE (1999 - 2007), HETE-2 (2000 - 2007), WMAP (2001 - 2010), INTEGRAL (2002 -), GALEX (2003 - 2013), Spitzer (2003 - currently in warm mission), Swift (2004 -), SUZAKU (2005 - 2015), AGILE (2007 -), FERMI (2008 -), WISE (2009 - NEOWISE), Herschel (2009 - 2013), and Planck (2009 - 2013). In this report, we first present a summary of each space mission, grouped by wavelength, along with selected science highlights. We also include a summary of the ground based observatories H.E.S.S., Veritas, Magic, and IceCube that contribute to observing and understanding high energy processes. Following the review of past and current missions, we present brief introductions to possible future missions, which would very significantly extend our knowledge of the Universe. We have not included the many balloon observations that have been obtained and, although ground-based radio and optical/IR observations are critical to understanding high energy astrophysics, the review of these radio and optical/IR observatories is covered by the reports from other IAU Divisions. We also do not include the many space missions that have observed the Earth.

2. Space astronomy missions, since 1994, that observe in the UV, Optical, or IR

2.1. *Hubble Space Telescope (HST) - (1990 - present)*

The Hubble Space Telescope was released into orbit on April 25, 1990 from the space shuttle Discovery. During the intervening 25 years, four Shuttle missions corrected the

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imaging capability to its current excellent state, added new science instruments, and replaced gyroscopes and batteries, allowing HST to maintain a leading role at the forefront of astronomical discoveries. Current HST instruments include the Wide Field Camera, the Space Telescope Instrument Spectrograph, the Advanced Camera for Surveys (ACS), and the Cosmic Origins Spectrograph.

HST has contributed to our scientific knowledge in nearly all areas of astrophysics, from measurments of water vaper in the atmospheres of exoplanets to studies of high redshift (z $\sim$10) galaxies and AGN. Observations of nearby galaxies have led to a fuller understanding of the life cycles of star clusters, from their birth in molecular clouds to becoming part of the field star population. Deep images obtained for the COSMOS fields, the CANDELS survey, the CLASH survey, the Hubble Ultra Deep Field, and the on-going imaging of the six Frontier Fields allow studies of galaxy formation and evolution over cosmic time. The magnification provided by cluster lensing in the Frontier Fields allows HST to reach the depths that JWST will probe. HST observations also led to the discovery of more than 20 distant Type Ia supernovae, which increased significantly the accuracy to determine the history of cosmic expansion over the last 10 billion years, which showed that Dark Energy is the major component of our Universe. One of the most iconic images from Hubble is that of the "Pillars of Creation" in the Eagle Nebule (see Fig. 1). The Hubble visible light image (Fig. 1 left) provided a detailed view of the cold gas in these star-making pillars which are illuminated by the UV light from a cluster of young massive stars. In 2014 Hubble observed the Eagle Nebula again, but this time in the infrared (Fig. 1 (right). The bluish haze around the pillars is material that is being heated up and evaporating into space. XMM-Newton and Herschel views of a larger region around the Eagle Nebula are shown in Fig. 5.

2.2. *Infrared Space Observatory (ISO)- (1995 - 1998)*

ISO carried two spectrometers, a camera and an imaging photo-polarimeter. Among ISO's scientific discoveries is the detection of water vaper in many systems ranging from the atmosphere's of Jupiter, Saturn, Uranus, Mars, and the moon Titan, to the warm regions around high mass stars (e.g. Orion), to low mass stars and AGB stars, to cold dark clouds, to planetary nebula, to Sgr B2 region in the core of our Galaxy to Arp 220.

2.3. *Submillimeter Wave Astronomy Satellite (SWAS)- (1998 - 2004)*

The Submillimeter Wave Astronomy Satellite (SWAS) surveyed more than 5000 lines-of-sight toward more than 200 Galactic objects in transitions of five astrophysically important atomic and molecular species: H216O, H218O, O2, CI, and 13CO. SWAS sources include giant molecular clouds, dark molecular clouds and starless cores, diffuse and translucent interstellar clouds, planetary nebulae, supernova remnants, oxygen-rich evolved stars, extreme carbon stars, and solar system objects including Jupiter, Saturn, Mars and comets. SWAS also mapped warm dust clouds where star formation is occuring in the nearby galaxy M51.

2.4. *Far Ultraviolet Spectroscopic Explorer (FUSE)- (1999 - 2007)*

The Far Ultraviolet Spectroscopic Explorer (FUSE) was launched in June 1999 and through eight years of high resolution far-ultraviolet spectroscopic observations greatly increased our understanding in many areas of astrophysics. Significant scientific results include the detection of molecular hydrogen in the atmosphere of Mars implying that a large amount of water escaped in the past, determining abundances of deuterium, molecular nitrogen, and highly ionized oxygen in the interstellar medium of our Galaxy, and discovering the extended hot gas halo around our Galaxy.

Figure 2. The Spitzer image of the Sombrero galaxy (M104) shows the full ring of dust (in red) circling the galaxy. In visible light, only the near edge of the dust ring can be seen. Spitzer also observes the bulge region (in blue) and a inner disk of stars.

2.5. *Spitzer Space Telescope (SST) - (2003 - present)*

Following the success of ISO, the first space-based infrared observatory, the Spitzer Space Telescope (Spitzer) was launched in 2003 into an Earth-trailing solar orbit. The combination of low backgrounds and new detector technology enabled Spitzer's superb sensitivity and mapping speed. The volume of space probed by Spitzer in one day is more than that studied by IRAS in its entire lifetime. The spectroscopic reach of Spitzer (5 to 38 μm) has allowed detailed study of phenomena ranging from planets orbiting other stars to high redshift galaxies. Spitzer's deep imaging (3.6, 4.5, 5.8, 8.0, 24, 70 and 160 μm) has even detected galaxies at z$\sim$7.

Among its many discoveries and results, Spitzer demonstrated that mature galaxies exist at redshifts $z > 6$. It resolved the infrared background into individual galaxies and AGN, and enabled a census of these objects during the peak of star formation and galaxy formation activity at redshifts $1 < z < 2$. Spitzer generated arcsecond-resolution maps of more than 200 square degrees of the Milky Way, allowing a full accounting of all star formation in our Galaxy. It revealed the signature of dust formation in the ejected layers in the Cas A supernova remnant. Spitzer data have led to an understanding of the building of planetesimals in the circumstellar disks of young stellar objects. It has shown that solar system comets have a mineralogy similar to that of dust debris disks surrounding nearby stars. Spitzer collected data to characterize the physical properties of exoplanets including their density and gas/rock structure and surface temperature. Spitzer provided the first detection of water vapor absorption in an exoplanet atmosphere.

Spitzer has exhausted its Helium cryogen and is now operating in a "warm" mission phase carrying out observations at 3.6 and 4.5 μm with essentially the same sensitivity in these wavelengths as earlier in the mission.

2.6. *Galaxy Evolutions Explorer (GALEX) (2003 - present)*

Launched in April 2003, the Galaxy Evolution Explorer (GALEX) has performed extensive sky surveys and studies of galaxies with its wide field ($\sim$1.2 deg diameter) V cameras in the far UV ($\sim$1528 Angstrom) and near UV ($\sim$2310 Anstroms). The GALEX spatial resolution is $\sim$5". Although the GALEX mission lost its FUV detecter in May 2009, the NUV detector has continued to provide new results. The largest area GALEX surveys are

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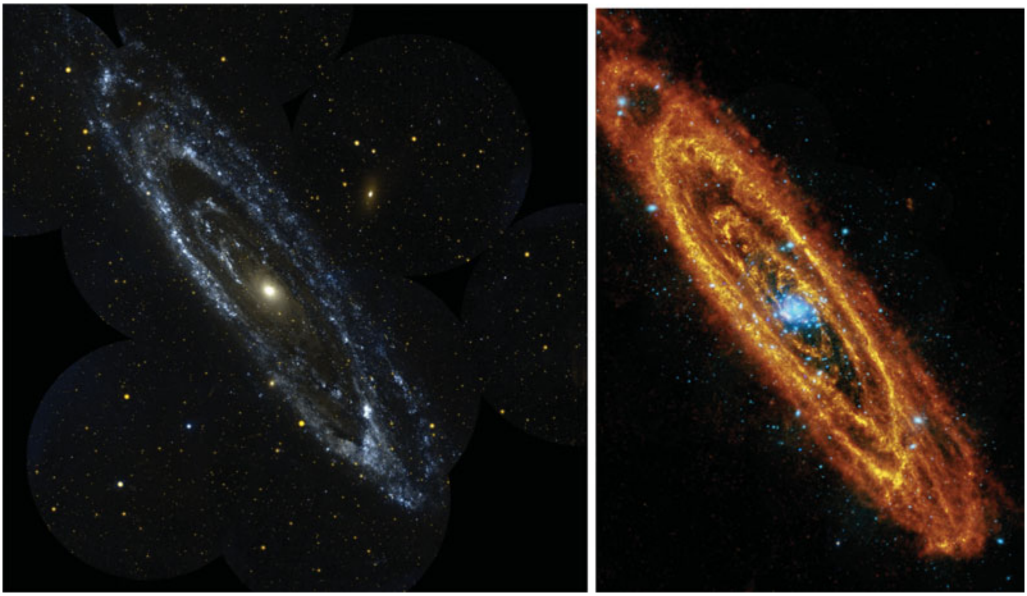

Figure 3. (left) GALEX image of the Andromeda galaxy showing bright star forming regions. (right) Herschel IR image showing the distribution of dust in the Andromeda galaxy.

the All-Sky Imaging Survey with exposure times of 100 seconds and the Medium-depth Imaging Survey with exposures of 1500 seconds. The Deep Imaging Survey of selected fields had exposures of several tens of thousands of seconds. GALEX also has imaged the Magellanic Clouds, providing a sensitive survey of hot stars, which shows young stellar populations even in regions with low star formation rates. The Nearby Galaxies Survey has observed more than 500 nearby galaxies. Fig. 3 (left) shows the GALEX image of the Andromeda Galaxy (M31). Discovered in the GALEX images of $\sim$30% of the spiral galaxies were tenuous UV disks of recent star formation, extending several times the optical size of the galaxies. UV bright ring structure were also found in some early-type galaxies. Finally, the several million stars detected in the UV in our Galaxy provide an unbiased census of hot white dwarfs and Planetary Nebulae. The GALEX database in 2013 contained measurements for more than 200 million sources.

Recently researchers using GALEX and HST observations measured the intensity behavior over the last 20 years of the two supermassive black holes in the quasar PG 1302-102, which orbit each other with a five year period, with velocities up to 7% the speed of light. In another recent scientific highlight, researchers using GALEX data combined with observations made by the Anglo-Australian telescope, confirmed that dark energy is driving the expansion of the Universe at accelerating speeds. GALEX was developed by NASA with contributions from the Centre National d'Etudes Spaliales of France and the Korean Ministry of Science and Technology.

2.7. *AKARI (ASTRO-F) (2006 - 2011)*

The first Japanese infrared satellite AKARI was launched in February 2006 surveyed 95% of the sky by November 2006. The mission continued after the boil-off of its liquid Helium coolant, by using active cooling to only 40K and restricting the long-wave IR observations. The first point source catalog with 1.3×10^6 sources was released in 2010. The all-sky images and the faint source catalogs were made publicly available in 2015. Besides the all-sky survey, about 5,000 pointed observations had been made for selected sky areas

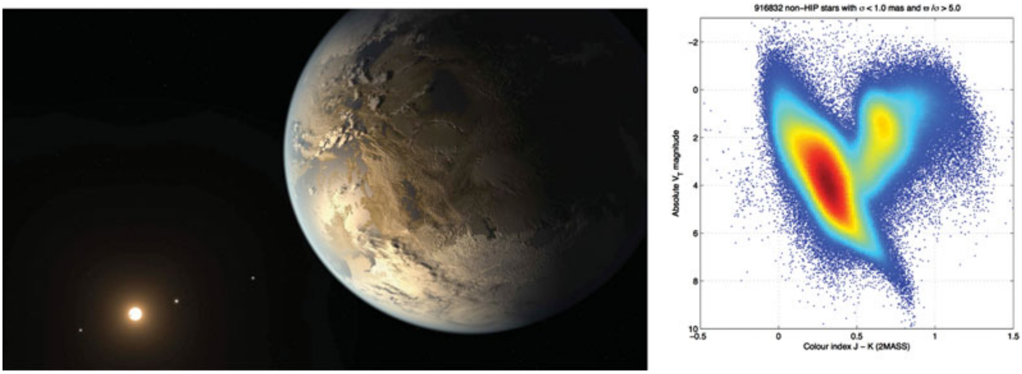

Figure 4. (left) An artist's representation of Kepler-186f, the first rocky exoplanet discovered by Kepler, within the habitable zone of a star similar to our Sun. (right) The H-R diagram based on the the first year of GAIA observations.

and individual sources, including planetary sources, young and old stars, galaxies, and the cosmic IR background. More than 12,000 pointed observations were made in the near-infrared. The observations were terminated in May 2011, but the data reduction and archiving activities are continuing.

2.8. *COnvection ROtation and planetary Transiets (COROT) (2006 - present)*

The CNRS and ESA COROT satellite was launched December 27, 2006 to study transiting exoplanets and stellar astroseismology. COROT observations led to the first detection of solar-like oscillations in stars other than our Sun. During its six years of operation, 32 exoplanets were discovered with COROT, with planet masses ranging from seven times that of the Earth to twenty times that of Jupiter.

2.9. *Kepler (2009 - present)*

The Kepler observatory was launched by NASA on March 7, 2009 with the scientific goal of determining the structure and diversity of planetary systems. In the 115 square degree field surveyed by Kepler, more than 1000 planets have been confirmed. Their diverse properties range from those of Kepler-186f (see Fig. 4), the first rocky exoplanet orbiting a star similar to our Sun and within the habitable zone (the region around a star where a planet's temperature would allow for liquid water), to Kepler-11 which has at least five planets within the orbit of Mercury, to those of Kepler-16b, which like the Star Wars planet Tatooine, orbits two stars. The recent discovery of Kepler-452b in which a super-Earth orbits a G type star is the best example so far of a planet-star system similar our own.

2.10. *Herschel (2009 - 2013)*

ESA launched the Herschel spacecraft, together with Planck, in May 2009. Its 3.5 meter diameter primary mirror is the largest astronomical telescope ever launched. Herschel is an ESA Corner-Stone Mission with instrument contributions by NASA. Two important local discoveries based on Herschel observations are the detection of water vapor from the dwarf planet Ceres in the asteroid belt and the determination that the deuterium to hydrogen ratio in the comet 103P/Hartley 2 is the same as water on Earth, supporting the hypothesis that Earth's oceans were formed at leased in part by contributions from comets. Two of Herschel's primary science objectives of Herschel were to study the formation of stars and galaxies, and to investigate the relationship between the two. At

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Figure 5. This composite far-infrared and X-ray image of the Eagle Nebula obtained by Herschel and XMM-Newton shows how winds from the hot, young stars seen in X-rays are sculpting and interacting with the cold gas and dust that is forming stars. Emission from the cold gas is seen by Herschel. Image coutesy of (far-infrared): ESA/Herschel/PACS/SPIRE/Hill, Motte, HOBYS Key Programme Consortium; and (X-ray:) ESA/XMM-Newton/EPIC/XMM-Newton-SOC/Boulander

low redshift, the Herschel image of Andromeda (see Fig. 3 right panel) shows rings of dust that trace gas reservoirs where new stars are forming as seen in the GALEX image in the left panel of Fig. 3. Hershel's survey of our own Galactic Plane shows pockets of gas and dust that were heated by newborn stars. Hershel has resolved the far infrared cosmic background, revealing AGN and starburst galaxies at the early epochs of star formation. Herschel follow-up observations of 234 Planck detected sources in the distant Universe showed that most of these sources were dense concentations galaxies that are forming stars at rates of a few hundred to 1500 solar masses per year, compared to a star formation rate of about one solar mass per year in the Milky Way.

2.11. *WISE (2010 - present)*

The Wide-Field Infrared Survey Explorer (WISE) mission was a NASA-funded Explorer mission carrying a 40-cm telescope and detectors cooled to 15K by solid hydrogen. It was launched in 2009 and ran out of cryogen on 29 September 2010. During this period WISE conducted a full survey of the sky in four IR bands: 3.1, 4.6, 12 and 22 μm. In October 2010, NASA extended the mission for four months with a program called Near-Earth Object WISE (NEOWISE) to search for asteroids and comets close to Earth's orbit. In

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March 2012, an atlas and catalog of the entire sky based WISE data was made public. Beginning in the fall of 2013, WISE began a three-year search for asteriods that could potenially collide with Earth.

Recent science highlights include the discovery of the most luminous known infrared galaxy in the Universe, where the emission is suggested to be due to the heating of a disk or corona in the galaxy's center by a supermassive blackhole.

2.12. *SOFIA (2010 - present)*

The atmospheric window for infrared observations opens up substantially at stratospheric altitudes, even though background emission remains a limiting factor. The Stratospheric Observatory for Far-Infrared Astronomy (SOFIA) is designed to exploit this opening by flying a 2.5 meter telescope on board a modified Boeing 747SP airplane; it is a joint venture of NASA and DLR, the German Aerospace Agency. The first science flight was in December 2010. Science highlights include studies of the star forming regions in our Galaxy, as well as the star forming region N159 in the Large Magellanic Cloud, protosteller outflows, and observations of Jupiter, Mars, Pluto and comets in our Solar System.

2.13. *GAIA (2013 - present)*

The ESA GAIA (Global Astrometric Interferometer for Astrophysics) mission, to follow-up and enhance the Hipparcos mission, was launched on December 19, 2013 and began routine operations on July 25, 2014. GAIA surveys stars and other astronomical objects to magnitude 20 with excellent astrometry with the goals of measuring stellar distances and motions through the Milky Way. In its first year, GAIA recorded 54 billion photometric data points, 272 billion positional measurements and 5.4 billion spectra. A catalog is planned to be released in summer 2016. GAIA's first H-R diagram based on the first year of data is shown on the right of Fig. 4. In addition to measuring the positions and motions of stars, the GAIA observations also allow each object's brightness to be determined, resulting in the discovery of many variable stars and hundreds of transient sources, including a cataclysmic variable and a supernova.

3. Space astronomy missions since 1994 that observe in the X-rays

3.1. *ROentgen SATellite (ROSAT)- (1990 - 1999)*

ROSAT was developed through a cooperative agreement between Germany, the United States and the United Kingdom. The satellite was designed and operated by Germany, launched by the United States and carried German, US and UK scientific instruments. ROSAT performed the first imaging full-sky X-ray and EUV surveys. The sky survey was followed by pointed observations. Source catalogs based on the all-sky surveys and the pointed observations contain more than 100,000 X-ray sources. These catalogs as well as the ROSAT data continue to be widely used today. From the detection of soft X-ray emission from the sunlit crescent of the Moon and from the Hyakutake comet to EUV observations of stars to very deep pointed observations that showed that more than 70 percent of the soft (0.5-2 keV) X-ray "background" is resolved into discrete sources, primarily Active Galactic Nuclei (AGN) and the extensive catalogs of clusters of galaxies, ROSAT contributed substantially to many areas of X-ray astronomy.

3.2. *The Advanced Satellite for Cosmology and Astrophysics (ASCA) (1993 - 2001)*

ASCA was Japan's fourth cosmic X-ray astronomy mission and the first to use X-ray CCDs. It was launched in 1993 and operated until 2001. The energy resolution provided by the CCDs (8% at 6 keV) led to important discoveries including that the asymmetry

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in the iron line emission from the relativistic accretion disk about AGN is due to strong gravitational effects close to the supermassive black hole. In addition, superluminal motions were found arising from X-ray jets in two microquasars (galactic binary systems containing a black hole).

3.3. *Rossi X-ray Timing Explorer (RXTE) (1995 - 2012)*

From 1995 to 2012, RXTE's high throughput and fast timing capabilities allowed the detailed study of X-ray variability on timescales from microseconds to months in the energy range from 2 to 250 keV for compact objects, most notably galactic black holes and neutron stars. RXTE observations were crucial for determining the millisecond timing properties of accreting neutron stars as well as finding rapidly spinning neutron stars in low mass X-ray binaries. RXTE's large throughput and fast timing ability also enabled researchers to argue that the black hole in the micro-quasar GRS 1915+105 is near maximal spin. In addition the QPO behavior in XTE J1650-500 led investigators to determine a mass for the black hole of only 5 M_{sun}, currently one of the smallest known black holes, along with GROJ0422+32, which has a similar, but more uncertain mass. Another of RXTE's major accomplishments was to show that Anomolous X-ray Pulsars and Soft Gamma-ray Repeaters are magnetars, neutron stars with very strong magnetic fields. Finally RXTE's long lifetime allowed recurrent transients such as the black hole system GX 339-4 to be studied during successive outbursts.

3.4. *BeppoSax (1996 - 2003)*

The BeppoSax mission was a major program of the Italian Space Agency (ACI) in collaboration with the Netherlands Agency for Aerospace Programmes (NIVR), designed to detect Gamma-ray bursts and study intensity and spectral variability of these bursts and other sources over the energy range from soft X-rays to Gamma-rays. Bepposax carried five science instruments, the Low Energy Concentrator Spectrometer operating in the 0.1-10 keV range, the Medium Energy Concentrator Spectrometer in the 2-10 keV range, the Phoswich Detection System in the 100-600 keV range, which had a large field of view for detecting Gamma-ray bursts, in addition to the High Pressure Gas Scintillation Proportional Counter which could detect X-rays up to 120 keV, and the Wide Field Camera which has two coded aperature cameras which detected X-rays in the 2 to 30 keV range and covered a 40 X 40 degree region of the sky. Science highlights include measurements of the heavily obscured (Compton-thick) nuclei in Seyfert 2 galaxies. These sources often show a reflection component from optically thick cold matter and less frequently reflection from ionized matter. A study of the BL Lac Markarian 501 found that the X-ray emission is due to synchrotron radiation and the TeV emission is from inverse Compton scattering of the synchrotron photons.

3.5. *Chandra (1999 - present)*

Since its launch in July 1999, the Chandra X-ray Observatory has been NASA's flagship mission for X-ray astronomy. With arcsecond angular resolution, Chandra has contributed to a wide variety of astronomical studies including 1) a detailed census and vivid picture of young stars in the epoch of planet formation in star forming regions. High-resolution spectroscopy of Sun-like stars has revealed the details of plasma conditions in multi-million degree coronae, finding a diverse pattern of chemical fractionation that is likely to be the signature of Alfv'en wave propagation; 2) mapping the X-ray emission and structure of clusters of galaxies to their virial radius and using clusters of galaxies to measure the growth of structure and to constrain cosmological parameters including σ_8 and the equation of state for dark energy; 3) providing very strong evidence for the

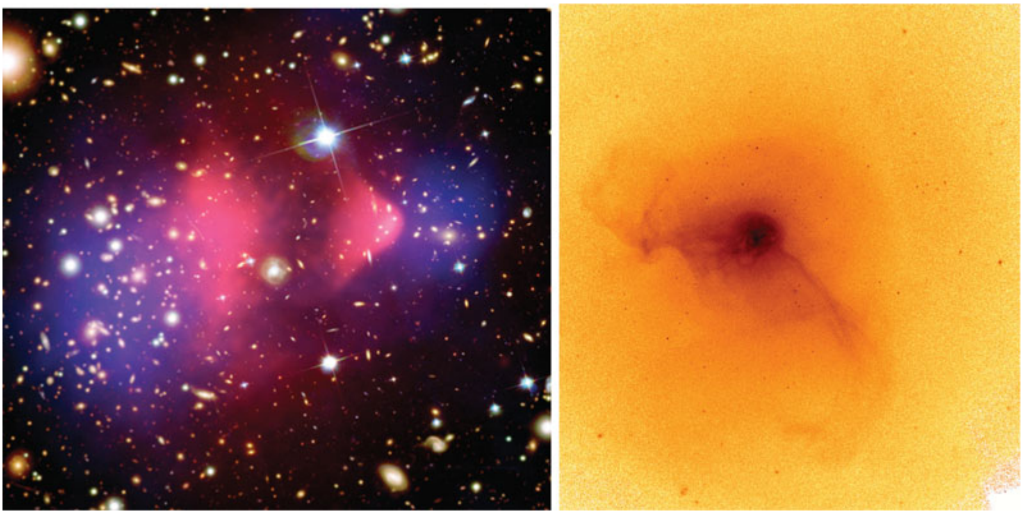

Figure 6. (left) The Bullet Cluster. Chandra detected X-ray emission in red, distribution of dark matter in blue superposed on optical image. (right) Chandra X-ray image of M87 in the core of the Virgo cluster.

existence of Dark Matter through X-ray and lensing observations of the Bullet cluster, which show the positional offset of the luminous X-ray emitting gas from the Dark Matter (see Fig. 6, left); 4) mapping the distribution of heavy elements in supernova remnants, constraining the physics of particle acceleration in shocks,and probing jet/taurus structures in pulsar wind nebulae; 5) measuring the size and intensity variability of knots in the jets from AGN; 6) determining the power, age, and most recently, the duration of AGN outbursts by measuring the shocks and cavities created by the AGN outbursts in the hot gas in galaxies halos and in clusters of galaxies (see Fig. 6, right); 7) production of a Chandra catalog containing 106,586 sources with a sky coverage of about 380 square degrees; and 8) through very deep observations, resolving most of the extragalactic X-ray background into sources and also resolving much of the Milky Way ridge emission into discrete sources.

3.6. *XMM-Newton (1999 - present)*

With its three co-aligned X-ray telescopes providing large collecting area, good angular resolution and good high energy response up to 12 keV, XMM-Newton has obtained high throughput X-ray imaging, timing and spectroscopy for a wide variety of astrophysical sources from comets and planets in our Solar System to very distant quasars and clusters of galaxies, since its launch in 1999. Its large field of view and large effective area allow large solid angle views of the X-ray sky. Fig. 7 shows one example, the large XMM-Newton survey of the Galactic center.

Examples of XMM-Newton's particularly notable accomplishments include 1) evidence of shock heating within magnetically-channeled winds in some stars revealed through high resolution spectroscopy; 2) XMM-Newton and Chandra studies of early-type stars have consolidated the framework of radiatively-driven shocks, and isolated examples of close binaries whose X-ray emission results from their colliding winds. High-resolution spectroscopy has revealed evidence of shock heating within magnetically-channeled winds in some stars. High resolution spectroscopy of nova events has also probed the radiatively-driven outflows of supersoft X-ray sources at the Eddington limit; 3) detailed studies of the spectra and large-scale structure of supernova remnants, including population studies

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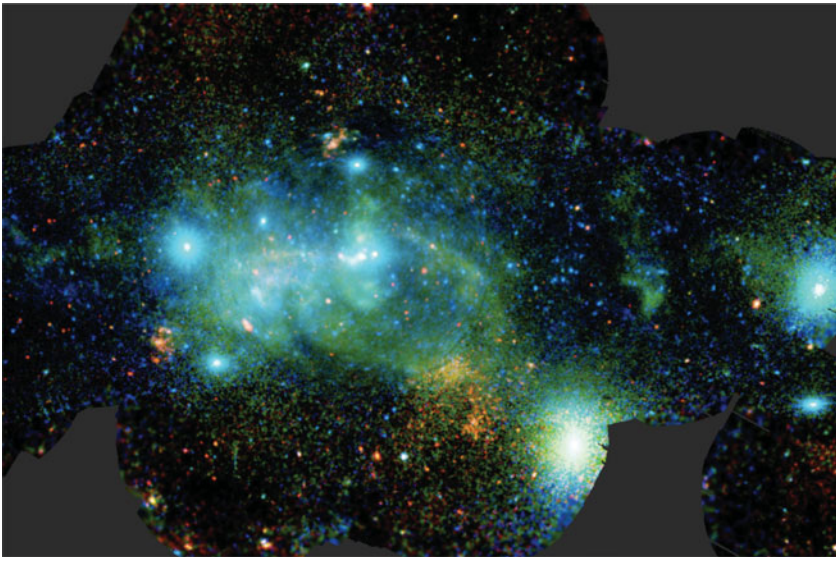

Figure 7. This mosaic of XMM-Newton observations shows the X-ray emission in a 1.5 deg × 2 deg region around our Galactic center. Sagitarius A is the X-ray bright region near the center of this image. The diffuse X-ray emission is due to a combination of hot gas and unresolved X-ray sources (CV stars and X-ray binaries). The large elliptical-shaped ring of X-ray emission southwest of the Galactic center is a bubble in the extended emission, created an outburst from the supermasive black hole in our Galaxy center, although supernovae explosions have also been suggested.

from mapping the Magellanic Clouds; 4) constraints on the spin as well as the mass of supermassive black holes in Active Galactic Nuclei (AGN); 5) the discovery of quasiperiodic oscillations (QPOs) in several ULXs; 6) the demonstration that cool gas is being uplifted by AGN produced bubbles from the cores of galaxy clusters; 7) the detection of X-ray luminous galaxy clusters to $z \sim 1.6$, bringing to more than forty the number of known clusters in the first half of cosmic time ($z \geqslant 0.8$), which allows a systematic look at the earliest formation history of the most massive objects in the Universe; 8) follow-up observations to confirm and characterize Planck SZ selected clusters; and 9) the release of the third XMM-Newton Serendipitous Source Catalog, or 3XMM, which contains 531,261 detections (372,728 unique sources) drawn from 7427 XMM-Newton EPIC observations that cover 794 square degrees on the sky.

3.7. *Suzaku (2005 - 2015)*

Suzaku, Japan's fifth X-ray astronomy mission, was launched in 2005 and ended operations in 2015. Although the X-ray Spectrometer (calorimeter) lost its cryogen shortly after launch, the X-ray Imaging Spectometer and Hard X-ray Detector continued to provide new observations until 2015. With its excellent CCD energy resolution in the soft X-ray range, its comparatively low intrinsic background due to the low-Earth orbit, and its unprecedented sensitivity in the hard X-ray band, Suzaku performed as a powerful wideband X-ray observatory. Science highlights include imaging spectroscopy of SNRs, our Galactic center, and cluster of galaxies that measured the density, temperature, and abundance distributions of the hot gas in these systems and measurements of the broad Fe-K lines from massive black holes which revealed the gravitational effects and determined the spin of black holes.

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3.8. *Monitor of All-sky X-ray Image (MAXI) (2009 - present)*

The Japanese MAXI (Monitor of All-Sky X-Ray Image) mission with a gas slit camera and a solid state camera, primarily designed to discover new X-ray transients, has been on the International Space Station since August 2009. In addition to finding five new black hole candidates, MAXI has detected 23 X-ray flares in 12 stars. A catalog of 500 high latitude sources found in the first 37 months of operation has been generated. Of the 296 identified sources, one third are clusters of galaxies and one third are AGN.

3.9. *Nuclear Array Spectrometer Satellite (NuSTAR) (2012 - present)*

NuSTAR, the Nuclear Array Spectrometer satellite, launched June 13, 2012, is the first focusing high energy X-ray mission, allowing sensitive studies of the hard X-ray sky (3 - 79 keV) that observe black holes, map supernova explosions and investigate the supermassive black holes in active galaxies. Fig. 11 shows the Recent NuSTAR observations led to the detection of five of nine targeted supermassive black holes that were thought to be active, but heavily obscured. NuSTAR observations also led to the discovery of a 3.76 second pulsating, transient Magnetar near our Galactic center as well as the discovery of an untraluminous pulsating neutron star in a binary system.

3.10. *Astrosat (2015 - present)*

India's first dedicated multi-wavelength astronomy satellite ASTROSAT was launched on September 28, 2015. A first-light image of the Crab Nebula taken on October 6 as well as detection of a Gamma ray burst have been released. The door of the Soft X-ray Telescope was opened October 26, 2015 allowing a first observation of the blazar PKS2155-304. Five instruments cover the spectral domain from hard X-rays to the visible. In particular Astrosat will cover the X-ray spectral band from 0.3 to 150 keV with three co-aligned X-ray instruments which are the soft x-ray imaging telescope, the LAXPC instrument for timing and spectroscopy, and the Cadmium Zinc Telluride Imager to study sources in the range from 10 to 100 keV. Simultaneous UV and optical coverage will be provided by two 40 cm telescopes. A Scanning Survey Monitor (SSM) will detect transient X-ray sources. Multi-wavelength spectroscopic studies and monitoring of the intensity variations of a wide variety of cosmic sources will allow detailed study of X-ray pulsars, X-ray binaries and AGN. The first six months of operations will be devoted to testing and calibration, followed by six months of observations by the mission team. After the first year, Indian scientists can propose for observing time, and after the second year, international scientists also will be allowed to propose observations.

4. Space astronomy missions since 1994 that observe in the Gamma-rays

4.1. *GRANAT - 1989 - 1994*

Granat was developed through the Soviet Space Program in collaboration with France, Denmark and Bulgaria and launched in December 1989. Its seven science instruments performed in the X-ray to Gamma-ray energies. Among its scientific accomplishments, Granat obtained very deep observations of the Galactic Center and discovered the first microquasar in our Galaxy (Granat source GRS1915+105).

4.2. *Compton Gamma-ray Observatory - 1991 - 2000*

The Compton Gamma-ray Observatory (CGRO) carrying four instruments that observed sources in the energy range from 20 keV to 30 GeV was launched in 1991 and operated

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until 2000. The all-sky map produced by the EGRET instrument shows bright diffuse emission along the plane of our galaxy produced by the interaction of cosmic rays and the intersteller medium, along with point sources, which include five newly discovered pulsars. CGRO also detected gamma-ray emission from blazars at cosmological distances, as well as gamma-rays from solar flares. The distribution of gamma-ray bursts on the sky supported their cosmological origin.

4.3. *HETE-2 - 2000 - 2007*

The High Energy Transient Explorer Mission (HETE-2) launched in 2000 was an international colaboration (US, Japan, France, and Italy) to study Gamma-ray bursts (GRBs) and identify their X-ray and optical afterglows. An important science highlight based on the HETE-2 detection of the short duration GRB050709, followed by Chandra and HST observations, was that such bursts was likely due to the merger of two neutron stars or a neutron star and a black hole.

4.4. *INTEGRAL - 2002 - present*

The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), an ESA mission in cooperation with Russia and the United States, was launched in October 2002 to study gamma-ray sources in the energy range from 15 keV to 10 MeV. INTEGRAL observations with the SPI spectrometer allowed researchers to study the 511 keV positron annihilation emission in our Galactic Center. In particular they found that the annihilation of positrons is occuring in warm (10^4 K) gas in the Galactic Center. INTEGRAL observations of Al^{26} at 1.8 MeV show Doppler shifted emission caused by the rotation of the Milky Way, thus leading to the conclusion that this emission is Galaxy-wide. INTEGRAL observations provided the first detection of gamma-ray lines associated with the ^{56}Co decay in the type 1a supernova SN2014j. INTEGRAL also discovered a population of obscured X-ray binaries with OB supergiants as their companion stars. Combined INTEGRAL, Chandra, XMM-Newton, HST and Swift observations led to the discovery of giant “bullets” of gas from the MKN509 black hole.

The fourth INTEGRAL catalog contains 723 sources, most of which are identified with black hole or neutron star binaries or with active galaxies, but 30% of the INTEGRAL sources are still unidentified.

4.5. *Swift - 2002 - present*

Swift’s fast scheduling ability and multiwavelength capability allows rapid X-ray and optical follow-up of new supernovae, variable stars, AGN outbursts and Gamma-ray bursts. Since its launch in November 2004, Swift has detected more than 1000 Gamma-ray bursts (GRBs), including about 30 short GRBs, with the highest redshift at z=6.3. The burst detected on March 19, 2008 made headlines as the first “naked eye” GRB when the optical emission from this redshift z=0.937 source reached 5.5 magnitudes. Swift also observed the supernova explosion of a giant star in January 2008, which was followed-up with Chandra, HST and ground based observations as well as extensive Swift observations. The BAT survey has detected 250 active galactic nuclei, with about 10-20% heavily obscured by dust. Also in non-GRB observations, Swift detected a giant flare from the young star EV Lacertae in April 2008, that was thousands of times more powerful than any observed from our middle-aged Sun.

4.6. *AGILE - 2007 - present*

The Italian AGILE (Astro-Rivelatore Gamma a Immagini Leggero) gamma-ray mission was launched in 2007 with the capability of simultaneously observing sources in the

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30 MeV to 50 GeV band and in the 18 to 60 keV hard X-ray band. In addition to imaging, AGILE provides sub-millisecond timing for the study of transient phenomena. Important scientific results include the discovery of a giant Gamma-ray flare from the Crab. Gamma-ray flares have also been detected from Cygnus X-1 and Cygnus X-3. In the pulsar PSR B1259-63, AGILE found non-thermal emission produced by high energy particles accelerated by a shock between the pulsar wind and circumstellar material. AGILE has also observed terrestrial Gamma-ray flashes (TGFs) from thunderstorms on Earth.

4.7. *Fermi - 2008 - present*

The Fermi Gamma-ray Space Telescope is an international mission launched in 2008 to observe the Gamma-ray sky from 30 MeV to 300 GeV with the Large Area Telescope (LAT), an array of sixteen towers that detect Gamma-rays and distinguish them from cosmic rays. Fermi also carries a Burst Monitor (GBM).

Gamma-rays have been detected and studied with Fermi from a wide variety of objects, including Eta Carinae where the Gamma-rays may be produced by colliding winds in this 5.5 year binary system, in addition to persistant Gamma-ray emission from SS433, and detections of sybiotic novae (e.g. V407 Cygni) and microquasars. Of particular note are the Fermi discoveries of more than one hundred Gamma-ray pulsars, including dozens of millisecond pulsars, some with orbital periods of less than 1 day. One of these is the millisecond pulsar PSRB1957+20 (one of the "black widow pulsars") where non-thermal emission produced by an intra-binary shock could contribute to unpulsed Gamma-ray emission. Fermi observations also lead to the observation that the Crab Nebula is not a stable X-ray or Gamma-ray reference source, confirming early results from Uhuru, and that the Crab showed intense flares and month-scale variations at hard X-ray energies (similar to AGILE results). Another major breakthrough based on Fermi data is the discovery of dozens of radio quiet neutron stars.

5. Ground-based gamma-ray observatories since 1994

5.1. *VERITAS*

Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four 12 meter Cherenkov telescopes that detect gamma-rays in the energy range from 50 GeV to 50 TeV. VERITAS is located at the Fred Lawrence Whipple Observatory in southern Arizona. VERITAS has detected very high energy gamma rays from several blazers and AGN. Prior to the VERITAS array, the Whipple 10m gamma-ray telescope operated from 1968 to 2013, detecting the first TeV gamma-ray source, the Crab Nebula, in 1989.

5.2. *H.E.S.S. and MAGIC*

Very high-energy (VHE) Gamma-ray astronomy has emerged as a truly observational discipline, largely driven by the European-led High Energy Stereoscopic System (H.E.S.S.) and the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope.

H.E.S.S. (the High Energy Stereoscopic System) is an array of four Atmospheric Cherenkov Telescopes located in Namibia that were operational at the end of 2003. A fifth, much larger telescope H.E.S.S. II became operational in July 2012. H.E.S.S. allows the study of gamma rays with energies from 10s of GeVs to 10s of TeVs and can detect sourses at levels of a few thousandths the flux of the Crab nebula. The primary goal of H.E.S.S. is to provide the observations needed for understanding the acceleration, propagation and interactions of high energy gamma rays. Recently H.E.S.S. observations allowed the first detection of large scale, diffuse TeV gamma-ray emission along the Galactic Plane. Deep observations of dwarf galaxies and our Galactic center were used to place new contraints on annihilating TeV mass dark matter. Scientists from 32 institutions in 12 nations form the H.E.S.S collaboration.

MAGIC is two 12 meter telescopes which detect Gamma-rays in the 25 GeV to 30 TeV range. It is located on La Palma, one of the Canary Islands, on the former site of the HEGRA Gamma-ray observatory, an array of six atmospheric Cherenkov telescopes. MAGIC science highlights include the detection of pulsed gamma-ray emission from the Crab pulsar and high energy cosmic rays from the quasar 3C279.

6. Submillimeter and radio astronomy space missions

6.1. *Wilkinson Microwave Anisotropy Probe (WMAP) (2001 - 2010)*

The cosmology mission COBE took great steps towards establishing the Big Bang cosmology, with the confirmation of the black body nature of the cosmic microwave background radiation and the first evidence of anisotropy in its brightness distribution. These milestones were awarded the Nobel Prize in 2007. The WMAP mission WMAP, launched in 2001 as the first astronomical observatory at L2 point, confirmed COBE's results with higher sensitivity and angular resolution. A simple cosmological model with only six parameters (matter density, baryon density, Hubble constant, primordial fluctuation amplitude, optical depth, and a slope for the fluctuation spectrum, fits both the WMAP temperature and polarization data, as well as the small-scale CMB data, light element abundances, large-scale structure observations, and the supernova luminosity/distance relationship. A combination of the WMAP and HST observations yielded a Hubble constant good to a few percent. Today we have an accurate cosmological model as a reference frame for further astrophysical studies of the early Universe.

6.2. *Planck (2009 - 2013)*

The Planck Surveyor (Planck), an ESA mission with NASA contributions, carried out an all-sky survey covering nine wavelength bands from the far infrared to the radio (350 μ to 1 cm). Launched with Herschel in May 2009, Planck dramatically improved measurements of the intensity and polarization of the Cosmic Microwave Background (CMB), the relic radiation from the Big Bang. About 380,000 after the Big Bang, the Universe has cooled to where it is transparent to the CMB radiation. The CMB (see Fig. 8 (left)) shows small temperature fluctuations that correspond to regions that have slightly different densities at early times.

Analysis of the fluctuations in the CMB allows one to determine the composition and evolution of the Universe from its birth to the present. Analysis of the Planck observations (see Fig. 8 (right) yields a model for the Universe where normal matter makes up 4.9% of the total mass/energy, Dark Matter makes up 26.8% and dark energy contributes the largest share at 69.2%. The Hubble constant derived from Planck is 67.8 km/sec/Mpc which implies an age for the Universe of 13.8 billion years, with the era of reionization at a redshift of 8.8. However, Planck also detected an asymmetry and an extended cold spot in the CMB temperature map that are not expected in the standard model of the Universe. In addition to mapping the distribution of the CMB on the sky, Planck observations have led to several important catalogs of astronomical objects including clusters of galaxies selected through the Sunyaev-Zeldovich effect, compact sources and Galactic cold clumps.

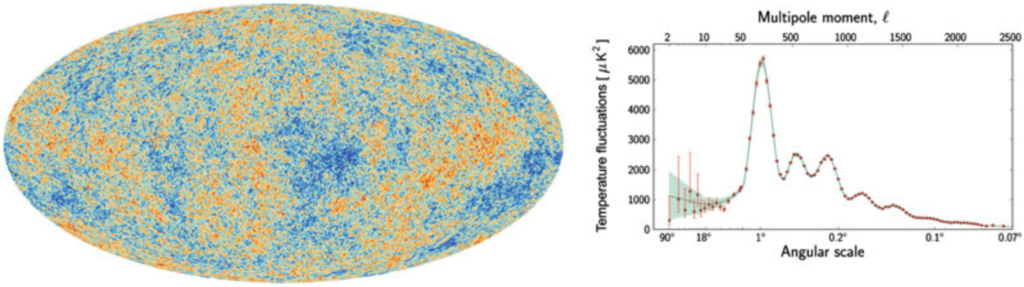

Figure 8. (left) The full sky map of the cosmic microwave background observed by Planck, after foreground contamination, primarily from our Galaxy, has been removed. (right) The power spectrum of temperature fluctuations in the Planck map (red) and the best fit model.

7. Ultra high energy cosmic rays and neutrinos

7.1. *Pierre Auger Observatory (1998 - present)*

Cosmic rays of ultra-high energy remain one of the least understood phenomena in the Universe. The Pierre Auger Observatory, a 3000 km^2 particle array combined with four wide-angle optical telescopes of atmospheric fluorescence light, located in the province of Mendoza, Argentina has demonstrated the existence of a statistically significant spectral feature (steepening or cutoff) at around 5×10^{19} eV, which is interpreted as marking the limiting energy of the most powerful cosmic rays. Also, a possible correlation between the arrival directions of the highest energy cosmic rays, above $\sim 6 \times 10^{19}$ eV, and the positions of nearby AGN has been reported. Since 1998 more than 500 scientists from 16 countries have carried out reseach using the Pierre Auger Observatory.

7.2. *IceCube (2010 - present)*

IceCube, the South Pole Neutrino Observatory, is a particle detector that records the interactions of the nearly massless astrophysical neutrino, which is produced by the most energetic sources in the Universe, such as supernova explosions and gamma-ray bursts. IceCube is the world's largest neutrino detector, encompassing a cubic kilometer of ice! IceCube has searched for and confirmed the presence of extragalactic muon neutrinos which reached IceCube by passing through the Earth. The detection of cosmic neutrinos may lead to understanding the origin of the highest energy cosmic rays.

8. Detection of high-energy particles

8.1. *Advanced Composition Explorer (ACE) (1997 - present)*

ACE (the Advanced Composition Explorer) was launched in 1997 and from its L1 location continues to detect high energy particles accelerated by the Sun, as well as particles accelerated in the heliosphere and galactic regions, with near real time 24/7 coverage of space weather, providing about one hour advance warnings of geomagnetic storms. Studies with ACE include determinations of the elemental and isotopic composition of the the solar corona, the solar wind and the local interstellar medium.

8.2. *Payload for Antimatter Matter Exploration and Light-nuclei Atrophysics (PAMELA) (2010 - present)*

The PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) detector has been orbiting Earth on the Resurs-DK1 Russian satellite since June 2010. Among the highlights of this mission is the discovery of antiprotons in the

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Van Allen belt. These are produced when antineutrons, produced by the collisions of cosmic rays with atoms in the upper atmosphere decay. Recently a new upper limit on strange quark matter abundance in cosmic rays was obtained from Pamela data.

8.3. *Alpha Magnetic Spectrometer (AMS-02) (2011 - present)*

In May 2011, the Alpha Megnatic Spectrometer (AMS-02) was mounted on the International Space Station to measure antimatter in cosmic rays and search for evidence of dark matter. In four years, AMS-02 has recored more than 60 billion cosmic ray events. The recent AMS Collaboration results on the antiproton to proton ratio, the electron spectrum and the combined electron and positron spectrum are consistent with dark matter collisions and cannot by explained by collisions of cosmic rays or known astrophysical sources.

9. Radio Observations from Space - RadioAstron 2011 - present

The space radio interferometry mission RadioAstron (Spekr-R, in Russian) was launched in July 2011 to a highly elliptical orbit with an apogee higher than 350,000 km. This is the first of the Russian large space observatories in the Spectrum (Spektr) series to reach orbit. RadioAstron carries a 10-m segmented dish, which was deployed in-orbit, and operates at wavelengths from 1.35-cm to 92-cm and, together with ground-based radio observatories, offers unprecedented angular resolution, as fine as 10^{-6} arcsec. First light was on 27 September 2011, when Cassiopeia A was observed at 92 and 18-cm. The current international science program includes the study of the inner-most regions of AGN jets, the milli-parsec jet in M81, as well as high resolution studies of water masers.

10. Space Missions in the IR, UV and optical in preparation or under study

10.1. *CHEOPS (CHaracterizing ExOPlanet Satellite (launch 2017)*

ESA's CHEOPS mission is designed to search for exoplanets using high precision photometry of bright stars known to host planets. For planets with known masses in the super-Earth to Neptune range, CHEOPS will determine their radii. Launched is planned for 2017.

10.2. *James Webb Space Telescope - JWST (launch 2018)*

James Webb Telescope, scheduled for launch in October 2018, will observe a wide variety of objects from planets in our Solar System to very distant galaxies in the infrared. With a 6.5 meter mirror (seven times the area of the Hubble Space Telescope), superb image quality, large field of view and low background, JWST will allow us to study the faintest stars and the most distant galaxies. Instruments include the Near-Infrared Spectrograph (NIRSpec) which will simultaneously measure the spectra of more than 100 objects. Key scientific objectives are to determine the star formation and chemical abundances in the most distant galaxies, tracing the creation of the elements over time, and in the local Universe, characterizing the atmospheres of extrasolar planets. The Mid-Infrared Camera and Spectrograph (MIRI) will study distant stars, regions of star formation hidden by dust, Kuiper belt objects and comets. JWST is a partnership between NASA, ESA and the Canadian Space Agency.

10.3. *Euclid (launch 2019)*

ESA selected in 2011 the Euclid mission to map the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts of ~2. Euclid is optimized for two primary cosmological probes: weak gravitational lensing and Baryonic Acoustic Oscillations (BAO). Euclid will operate from the L_2 point and will use a modified Korsch telescope with a primary diameter of 1.2-m, and central obscuration 0.4-m. The visible channel will use a 600 Mpixel CCD mosaic that will image a field of view of 0.5 square degrees with 0".2 pixels. The near-IR channel will use a 7.5 Mpixel mosaic to provide photometry from 0.9 to 2.0 μm. Euclid is now scheduled for a 2019 launch.

10.4. *SPICA (launch ~2020)*

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a proposed Japanese-led mission with extensive international collaboration (ESA, Korea, etc.). SPICA is optimized for mid- and far-infrared astronomy using a cryogenically-cooled 3.2-m telescope. Its high spatial resolution and unprecedented sensitivity will enable addressing a number of key problems, ranging from the star-formation history of the Universe to the formation of planets. To reduce the mission mass, SPICA will be launched at ambient temperature and will be cooled down on-orbit using on board mechanical coolers together with an efficient radiative cooling system. This combination allows a 3-m class space telescope cooled to 6K with a moderate total weight (3700 kg). The target launch year of SPICA is around 2020 for a five-year or longer mission.

10.5. *Spektr-UV (launch ~2021)*

Russia, Spain and Germany are developing a UV mission that would have a 1.7 meter telescope and three instruments, which are a High Resolution double eschelle spectrograph, a long-slit low resolution spectrograph and an imaging and slitless spectrograph for surveys.

10.6. *PLAnetary Transits and Oscillation of stars (PLATO) (launch 2024)*

ESA's PLATO mission, planned for launch in 2024, will search for exoplanets and measure stellar oscillations.

10.7. *Wide Field Imaging Survey Telecsope (WFIRST) - (launch ~ 2025)*

NASA's Wide Field Imaging Survey Telescope - Astrophysics Focused Telescope Assets (WFIRST-AFTA mission is planned for launch in the mid 2020's. It will carry two science instruments, 1) the wide-field camera, a 288 megapixel camera with a 0.28 sq degree field of view in infrared bands, from 0.7 to 2 microns and 2) a chronograph covering 0.4 to 1.0 micrometers with a primary science goal of detecting exoplanets near bright stars. WFIRST will also study Dark Energy through weak-lensing observations the detection of high redshift supernova and through baryon acoustic oscillations.

11. X-ray and Gamma-ray space missions in preparation or under study

11.1. *Astro-H (launch 2016)*

The X-ray observatory mission NeXT was approved by JAXA to be launched in 2016 and has been renamed Astro-H. A major new capability of this observatory will be high

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resolution spectroscopy of E/dE >1000 at 6 keV. Astro-H will also provide X-ray imaging up to 60 keV. Astro-H will make significant advances in many fields, including measuring the gas turblence in clusters of galaxies.

11.2. *Spectrum-X-Gamma (launch 2017)*

The Russian-German Spectrum-X-Gamma (SXG) mission is currently under construction. SXG will carry two powerful telescopes with imaging instruments, eROSITA (extended ROentgen Survey with an Imaging Telescope Array)and ART-XC. Launch into an L2 orbit will be in 2017. The first four years of the mission will be devoted to surveys of the entire sky, while the next 3.5 years will be used for pointed observations. eROSITA and ART-XC will perform deep surveys of the entire sky. eROSITA's sensitivity will be more than thirty times that of ROSAT in the 0.5-2 keV band. Its best imaging, on-axis, spacial resolution will be 15, "while the average blurring in the survey will be 28". ART-XC's energy band (6 to 30 keV) will provide the first high energy map of the full sky. Due to the scan pattern, the highest sensitivities will be at the ecliptic poles.

eROSITA's sensitivity will result in a wealth of X-ray information on newly discovered clusters of galaxies, groups, galaxies, AGN, stars and compact objects. All massive clusters of galaxies in the Universe will be detected in the all-sky survey. Approximately 1100 clusters will be at $z \geqslant 1$. In addition, tens of thousands of groups within 1 Gpc will be detected and used to trace large-scale filaments and to determine the outburst frequency and power of supermassive black holes. Three million AGN will be discovered, allowing a full census of radio and Seyfert galaxies, quasars and blazars. In addition the X-ray emission from several 10^6 stars, including stellar flares, will be detected and quantified. Finally these observations will form the basis for the most complete X-ray luminosity function for Galactic X-ray sources. These very large samples of clusters, AGN, stars and galactic sources will allow the most interesting and rare objects to be discovered.

The hard X-ray sensitivity of ART-XC telescope and instrument will lead to the detection of several thousand AGN, including the heavily absorbed Compton-thick AGN. The ART-XC also will allow detailed studies of Galactic sources up to 30 keV and images of bright clusters, including the detection of merger shocks.

11.3. *The Space multi-band Variable Object Monitor (SVOM) (launch 2021)*

The SVOM mission is a Chinese/French collaboration to investigate Gamma-ray bursts. The Gamma-ray detector ECLAIRs is a wide-field, coded mask camera that images the sky in the 4 to 120 keV range. Within five minutes of the detection of each burst by a Gamma-ray detector, onboard X-ray and optical telescopes will begin to study the afterglow and determine better coordinates for the burst. Of particular interest are very high redshift bursts and soft, faint nearby bursts. During the three year lifetime of the mission, 200 Gamma-ray bursts are expected to be detected. Launch is planned for 2021.

11.4. *Advanced Telescope for High Energy Astrophysics (ATHENA) (launch 2028)*

ESA is preparing the ATHENA X-ray observatory for launch in 2028. ATHENA will carry a large collecting area telescope with 5" angular resolution and state of the art X-ray detectors. ATHENA will observe the hot and energetic Universe, answering fundamental questions related to the formation of large scale structure and the role of supermassive black holes in galaxy formation and evolution. Athena is now in a study phase, where mission design and costing will be completed, before construction begins in $\sim$2019.

11.5. *X-ray Surveyor*

The X-ray Surveyor is currently under study as a possible future NASA mission. This mission would have Chandra-like spatial resolution, specifically 1 arcsecond angular

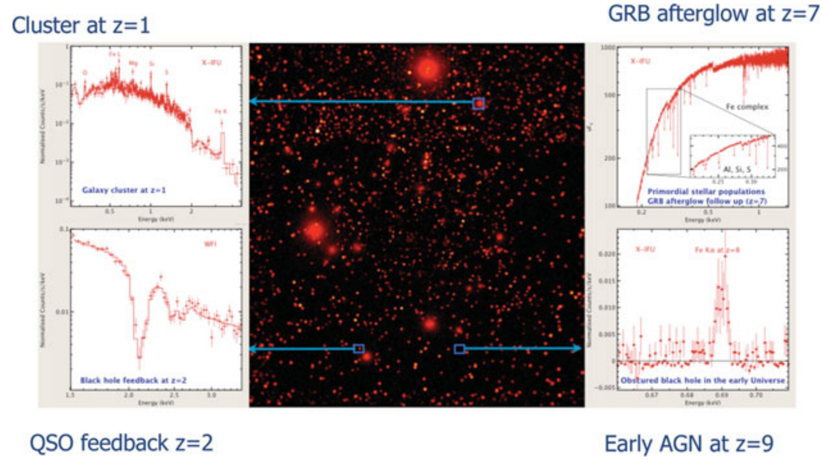

Figure 9. The center of this image shows a simulated deep survey for the ATHENA mission, along with simulated X-ray spectra for high redshift objects that will be found in ATHENA observations. These include a z=1 cluster of galaxies, the X-ray afterglow of a Gamma-ray burst, and a very high redshift AGN.

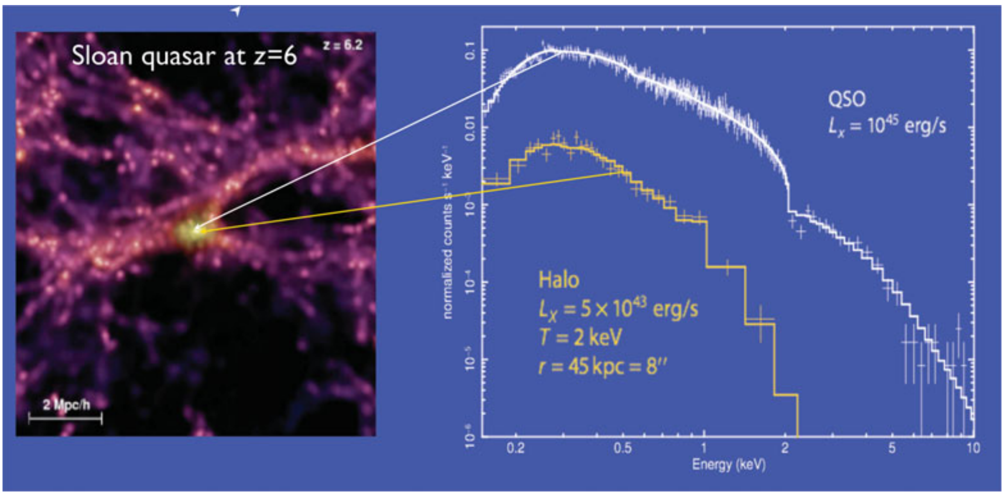

Figure 10. (left) A snapshot of part of the Millenium Survey at redshift 6, when the Universe is only one billion years old. Most quasars, like the one at the center of the image, are radiatively bright and in environments of galaxy groups (right) The spacial resolution and sensitively of an X-ray Surveyor mission will allow one to map the hot gas in the local environment of the quasar and measure the spectrum of both the quasar and the surrounding gas.

resolution over the field of view, but with ~ 50 times Chandra's collecting area. Possible science instruments are a microcalorimeter with a 5'×5' field of view and 1 arcsecond pixels, a large field of view (22' × 22') CMOS detector with 0.33 arcsecond pixels, and gratings to provide high resolution spectra. Like Chandra and XMM-Newton, the science areas which the X-ray Surveyor would address are very broad, ranging from detailed spectroscopy of nearby stars and supernova remnants to measuring the gas density, temperature and heavy element abundances in large scale gas filaments between clusters of galaxies (see Fig. 10) to determining the nature of the gas surrounding high redshift quasars.

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12. Gravitational wave missions in preparation or under study

The LISA Pathfinder, scheduled for launch in December 2015, is ESA's demonstrator for space-based observations of gravitational waves. The Pathfinder will place two small gold-plantinum cubes in nearly gravitational free-fall through space and then measure their motions. This will test critical concepts and technologies required for the detection of gravitational waves. The current version of LISA is now known as eLISA and is a candidate for an ESA L3 mission with a tentative launch date of 2034, as part of ESA's Cosmic Vision program.

13. Future cosmic ray mission - Japanese Experiment Module-Extreme Universe Space Observatory (JEM-EUSO)

A cosmic ray instrument on the International Space Station called JEM-EUSO (Japanese Experiment Module-Extreme Universe Space Observatory) is planned to be placed on the International Space Station in 2017 as an international collaboration under Japanese leadership. The instrument will detect flashes of light in the Earth's atmosphere caused by the interaction of an extremely energetic cosmic ray with an air atom. Observing the resulting track of the air shower will allow scientists to determine the energy and direction of the primary particle.

14. Possible Future ESA missions currently under study

ESA began a two year study of three missions in June 2015, with the goal of selecting one for flight in 2025. These are ARIEL (Atmospheric Remote-Sensing Infrared Exoplanet Large-survey) which would determine the chemical abundances and physical conditions on nearby exoplanets, THOR (Turbulence Heating ObserveR) which would address problems in the area of space plasma heating and dissipation of energy, and XIPE (X-ray Imaging Polarimeter Explorer) which would investigate the behavior of matter under extreme conditions through measurements of the X-ray polarimetry of supernova, jets, black holes and neutron stars.

15. Investigating our Solar System - Observing the Sun and heliosphere

15.1. *Yohkoh satellite (1991 - 2001)*

Japan's Yohkoh satellite observed X-rays from solar flares for an entire solar cycle. Scientists identified different types of flares learned that the Sun even in regions away from flares was more active than previously believed.

15.2. *Ulysses Solar Mission (1991 - 2008)*

Ulysses, a joint ESA/NASA mission, carried ten detectors in an orbit that viewed the Sun's poles in a mission that lasted almost 20 years. Quoting Ed Smith, NASA's Ulysses Project Scientist, "Ulysses redefined our knowledge of the heliosphere and went on the answer questions about our solar neighborhood we did not kow to ask." Ulysses observations showed that the Sun's magnetic field is carried into the Solar System in a complicated manner so that particles can travel from low to high latitudes and vice versa.

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15.3. *WIND (1994 - Present)*

NASA's Wind satellite, launched in November 1994, measures the mass, momentum and energy of the solar wind from a "halo" orbit at L1. Wind has since been moved to other orbits including the second Lagrange point L2, to measure the properties of the magnetotail. In 2004, WIND was moved back to L1. Wind carries eight experiments, six to study the solar wind and two to dectect and study Gamma-Ray bursts. WIND, along with 17 other missions, including ACE, comprise the Heliophysics Systems Observatory. Wind has enough fuel to keep it in orbit at L1 until 2074.

Observations from NASA's ACE and WIND observatories and ESA's Cluster mission were used to discover a jet of charged particles in the solar wind extending at least 390 Earth radii. On February 2, 2002, during a time period of about two and a half hours, all three observatories detected, in sequence, a stream of charged particles. Such extentive jets are formed through the magnetic reconnection of interplanetary magnetic field lines carried by the solar wind which allows some of the energy of the magnetic field to be converted to particle energy.

Wind is one of the missions in the ISTP (International Solar-Terrestrial Physics) program which also includes GEOTAIL, POLAR, SOHO, and Cluster.

15.4. *Solar and Helioshperic Observatory (SOHO) (1995 - present)*

The SOHO mission was a cooperative effort between ESA and NASA, designed to study the internal structure of the Sun as well as its atmosphere to determine the origin of the solar wind. SOHO operates together with the Advanced Composition Explorer (ACE) also at L_1 and with the two STEREO spacecraft, one ahead of Earth in its orbit, the other trailing behind, to provide panoramic views of almost the entire solar surface. SOHO provided the first images of the Sun's convection zone, measured the acceleration of the slow and fast solar winds, and played a leading role in the early warning system for space weather.

15.5. *Transition Region and Coronal Explorer (TRACE) (1998 - 2010)*

launched in April 1998 by NASA revealed small scale features and motions in the solar photosphere and the transition region to the corona. The telescope had a 30 cm aperature and a CCD detector and obtained images from the optical to the far ultraviolet. The Sun's magnetic field structure can be determined from images of the solar plasma taken at wavelenths emitted or absorbed by ions formed at different temperatures.

15.6. *Reuvan Ramaty High Energy Solar Spectroscope Imager (RHESSI) (2002 - present)*

RHESSI's goal was to explore the basic physics of particle acceleration and the explosive release of energy in solar flares. RHESSI combines for the first time high resolution imaging in hard X-rays and Gamma-rays with high resolution spectroscopy, allowing a detailed spectrum to be measured for each part of the image. Thus where particles are accelerated and to what energies can both be determined. The combination of RHESSI observations with "white light" observations which contain a significant fraction of the flare energy, shows a non-linear correlation between the white light and hard X-ray fluxes, and no correlation with the X-ray spectral index. Thus the highest energy photons play only a minor role in the production of the white light. RHESSI observations of the quiet Sun suggest steady heating is more important than flare heating.

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15.7. *Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) (2003 - 2008)*

CHIPS performed an all-sky survey of the diffuse background in the extreme ultraviolet (90 to 260 Angstrons) with a primary goal of obtaining a spectrum of the expected hot, one million degree, gas in the local interstellar medium. However, the predicted hot gas was not detected. The strong limits set by the CHIPS observations imply that the gas is not at the predicted temperature, is significantly depleted in iron, or the emission is absorbed by neutral gas. From 2006 to 2008, CHIPS performed nearly 1450 observations of the solar disk. The spectra show a 1 to 2 MK plasma, dominated by iron emission. Temporal variations of up to 25% with a period of 27.2 days (the solar rotation period) were found. During these two years the spectra remained relatively stable, even during a moderate (M-class) flare.

15.8. *Solar Terrestrial Relations Observatory (STEREO) (2006 - present)*

Two spacecraft were launched so that combining their observations allowed stereoscopic studies of the Sun and coronal mass ejections.

15.9. *HINODE (2006 - present)*

The joint Japanese- NASA-UK (STFC) Hinode satellite, a Solar mission with a 0.5 meter optical and soft X-ray telescopes and an EUV imaging spectrometer was launched in September 2006. Its primary mission is to understand processes in the Solar magnetic field generation and transport.

The high (0.2″) spatial resolution of the telescopes has led to several important discoveries including finding that Alfven waves in the corona have sufficient energy to continuously launch the outflowing plasma as the source of the solar wind. In addition, oscillations in fine structures in the magnetic fields of prominances and sunspots, caused by Alfven waves, lead to coronal heating. Hinode observations also led to the conclusion that the numerous X-ray jet structures observed are the results of magnetic reconnections and are major contributors to driving the outflow of hot plasmas, which flow into the upper corona along open magnetic field lines. Researchers are now using Hinode and NuSTAR observations to better determine where the energy from the flare is released (see the combined Hinode-NuSTAR solar image in Fig. 11).

15.10. *Interstellar Boundary Explorer (IBEX) (2008 - present)*

The Interstellar Bounday Explorer (IBEX), one of NASA's Small Explorer missions, was launched in 2008 to examine how the Sun's heliosphere interacts with the interstellar medium outside the heliosphere. The design and operation of the mission is led by the Southwest Research Institute with Los Alamos National Laboratory and Lockheed Martin Advanced Technology Center as co-investigator institutions. Recently, scientists using IBEX data, as well as a reanalyis of the earlier Ulysses data, determined that the interstellar gas is hotter than previously found, and also determined the direction and how fast the heliosphere is moving through the interstellar material. As IBEX PI David McComas announced these results "open a completely new window on the local interstellar environment, its composition, its properties, and the likely processes at work in the interstellar space around the Sun and in the heliosperic boundary region."

15.11. *Solar Dynamics Observatory (SDO) (2010 - present)*

SDO, the Solar Dynamics Observatory, is the first mission in NASA's Living with a Star Program and was launched in February 2010. SDO is obtaining observations of the solar atmosphere on small angular scales and in several wavelengths simultaneously. Primary goals are to understand how the Sun's magnetic field is generated and structured and to

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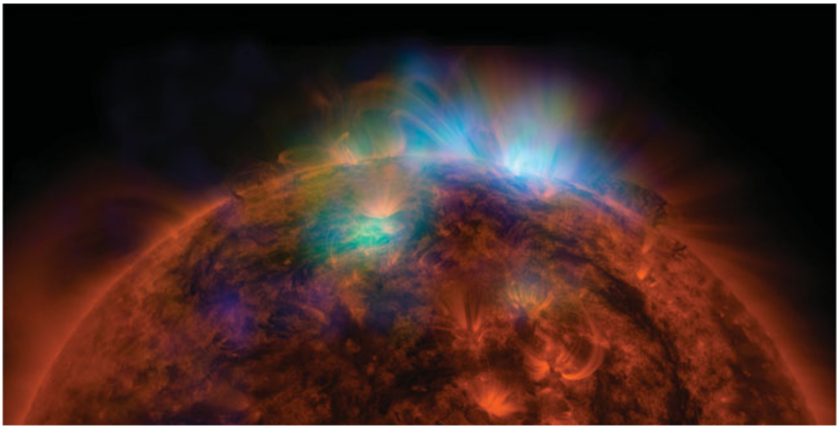

Figure 11. This image of the Sun shows the UV (171 angstrom) light from SDO in red and the hard X-ray emission from NuSTAR in green and blue.The image shows that some of the X-ray emission is from the active regions and coronal loops, while these regions appear darker in optical and UV light.

determine how this stored magnetic energy is converted and released by the solar wind, energetic particles and intensity variations, as well as what drives the Sun's 11-year cycle of activity.

15.12. *Interface Region Imaging Spectrograph (IRIS) (2013 - present)*

IRIS is a NASA Small Explorer Mission to observe how solar material either in the solar wind or in a coronal mass ejection, moves, gathers energy and heats up as it travels through the Sun's lower atmosphere.

16. Future solar missions in preparation or under study

16.1. *Solar Probe Plus (launch 2018)*

NASA's Solar Probe Plus will apporch within 3.8 million miles of the Sun to futher investigate what heats the solar wind.

16.2. *Solar Orbiter (launch 2018)*

The Solar Orbiter will have ten instruments and willl be in a highly elliptical orbit that will take it to within 43 million km of the Sun, closer than Mercury. The central question the Solar Orbiter will address is How does the Sun creat and control the heliosphere? During the planned seven year mission, the instruments will measure the properties of the solar wind plasma, fields and particles in close proximity to the Sun. Observation of the Sun's polar regions which are not visible from Earth will help to understand the Sun's internal dynamo. The Solar Orbiter mission is led by ESA with contributions from NASA.

16.3. *India's Aditya mission (launch 2018)*

The primary instrument on the Aditya mission will be a coronograph to study the dynamics of the Sun's corona.

17. Missions to planets in our Solar System

Since 1994, many missions have studied the planets in our Solar System. Here we present only a few of the many highlights from these missions.

Mars has been explored either from orbit or from the surface by several mission. NASA's MARS ODYSSEY was launched in 2001 and carried three primary instruments to measure the distribution of minerals on the planet's surface and to study the radiation environment. ESA's first mission to another planet, the MARS EXPRESS was launched in 2003. While the Mars EXPRESS carried out observations while orbiting Mars, the Beagle lander was lost. NASA's Mars Exploration Rovers landed on Mars in January 2004 to carry out geological investigations. They found that the plains of Meridiani on Mars were once water-soaked and discovered the mineral jarosite, which only forms in the presence of acidic water. The Curiosity Rover continues to explore and drill into the surface of Mars. The Mars Reconnaissance Orbiter (launched in August 2005) has found strong evidence that liquid waters flows intermittantly on the surface of Mars. The next Mars Rovers are planned for launch in 2020. The NASA Mars Maven mission was launched in late 2013 to explore the upper atmosphere and ionisphere of Mars. First scientific results presented in November 2015 suggested that solar storms eroded Mars's atmosphere nearly 4 billion years ago, leading to today's cold, arid planet. The first mission in the ESA ExoMars program will arrive at Mars in 2016 to search for evidence of methance and other gasses that could be signatures of active biological or geological processes.

The Cassini mission to Saturn, a joint endeavor of NASA, ESA and ASI, began orbiting Saturn in 2004 and included a probe to the largest moon, Titan. Some of the many science highlights from the Cassini mission are the determination of the internal structure of Saturn's moon Enceladus which is consistent with an ocean inside the moon, the discovery of a small icy object, that may be a newly formed moon, measuring the temperature and density structure of Titan's atmosphere, determining the impact on its atmosphere of storms on Saturn, jets from the surface of the moon Enceladus that spay icy particles that likely reach Saturn's outest E ring, and direct evidence of meteoriods breaking up when they encounter Saturn's rings.

The orbital exploration of Mercury by NASA's Messenger mission began in 2011 and showed the presence of small depressions with bright interiors and halos, often found in clusters. These could be actively forming today. ESA's Bepi Columbo mission to Mercury which will be launched in 2016 carries two orbiters, the Mercury Planetary orbiter and the Japanese Mercury Magnetosphere Orbiter.

NASA's New Horizons mission to Pluto was launched on January 19, 2006 and carried out a six month flyby of Pluto and its moons in the summer of 2015. New results include the finding that two of Pluto's mountains could be recently active ice volcanoes, that crater-free regions on the surface would indicate these regions formed in the last 10 million years, that Pluto has been geologially active during its history, and that Pluto's small moons are not rotating synchronously with the planet.

The Japanese mission Hisaki was launched in September 2013 to carry out UV observations of Venus, Mars and Jupiter. Akatsuki, an earlier mission, launched in May 2010, to study Venus was the world's first solar powered sail craft.

NASA's JUNO mission, launched in August 2011, will orbit Jupiter 33 times beginning in 2016. ESA is planning to launch the large mission, JUICE (Jupiter Icy Moon Explorer) in 2022 which will arrive at Jupiter in 2030. It will study Jupiter and three of its largest and potentially habitable moons, Ganymede, Callisto, and Europa.

17.1. *Missions to asteriods, minor planets and comets*

Spacecraft have also visited asteroids, moons and comets, in particular the NASA NEAR mission landed on the Eros asteroid, ESA's ROSETTA mission landed spacecraft Philae on the comet 67P/Churyumov-Gerasimenko, but it landed in a shadowed area and lost contact with Rosseta when its batteries lost power. The Rosetta spacecraft and its ALICE spectrograph continued to perform well. NASA is planning to launch the OSIRIS-REx mission in September 2016 to the asteroid Bennu and return samples in 2023.

Following a successful impact of its probe on comet Tempel 1, the DEEP IMPACT spacecraft now named EPOXI visited comet Hartley 2 in 2010.

The Japanese mission Hayabusa2 was launched in December 2014 to bring back samples from the asteroid Ryugu. The earlier Hayabusa mission returned particles from the asteroid Itokava in June 2010.

NASA's DAWN mission to explore two protoplanets in the asteriod belt began in September 2007. DAWN reached Vesta in 2011. NASA scientists concluded that Vest was the only remaining example of the large planetoids that formed rocky planets in our Solar System. The successful exploration of the minor planet Vesta mission is now being followed by a similar exploration of Ceres. DAWN will entered the its final orbit of Ceres to map the chemical elements on its surface in December 2015 and is expected to remain as a satellite of Ceres.

In 2020, NASA's OSIRIS-REx is planned to explore the near-Earth asteroid 1999 RQ36 and return samples from its surface.

18. Closing remarks

Today is an exciting time to be an astrophysicist. We are extremely fortunate to have operating space missions and ground based observatories that provide fantastic data across many wavelengths and allow us to address profound questions concerning the origin and evolution of the Universe and all types of celestial bodies and forms of matter within it. Most space missions and many ground based observatories provide rich archives, allowing broad community access to existing observations, often in conjunction with observations at other wavelengths, and often for purposes not imagined by the original observer. These treasure chests of archival data have led to many new discoveries.

Nearly every week, new worlds and new astrophysical phenomena are discovered. We continue to better understand the nearest star, our Sun, as well as the most distant galaxies, AGN and clusters. We have constrained cosmolological parameters, although the nature of both Dark Energy and dark matter still elude us. There is still much to be learned. New observatories are being planned and constructed that will provide answers to many of our questions. The excitement of astrophysical discoveries continues to excite scientists and the general public.