EXPLORATION OF JUPITER. F. Bagenal, Laboratory for Atmospheric & Space Physics, University of Colorado, Boulder CO 80302 (bagenal@colorado.edu)

Introduction: Jupiter reigns supreme amongst planets in our solar system: the largest, the most massive, the fastest rotating, the strongest magnetic field, the greatest number of satellites, and its moon Europa is the most likely place to find extraterrestrial life. Moreover, we now know of thousands of Jupiter-type planets that orbit other stars. Our understanding of the various components of the Jupiter system has increased immensely with recent spacecraft missions. But the knowledge that we are studying just the local example of what may be ubiquitous throughout the universe has changed our perspective and studies of the jovian system have ramifications that extend well beyond our solar system.

The purpose of this talk is to document our scientific understanding of the jovian system after six spacecraft flybys, Galileo's 34 equatorial orbits [1] and Juno's first 17 polar orbits of Jupiter [2], to review what we have learned about the planet, satellites and magnetosphere and to list outstanding questions.

Pioneers 10 & 11: As the era of space exploration blossomed in the late 1960s, engineers expanded their horizon past Mars to Jupiter and beyond. But before investing in sending expensive and delicate equipment two potential hazards needed to be evaluated. No spacecraft had ventured across the asteroid belt and while few were concerned about the very improbable collision with the large (but sparse) known asteroids, the distribution of dust and pieces of collisional debris was completely unknown. The second potential hazard to a spacecraft passing close to Jupiter was its radiation belt. Three years before Van Allen's 1958 historic discovery of the radiation belts around the Earth, powerful radio emissions from Jupiter were detected [3]. By the late 1960s it was clear that Jupiter's radio emissions were generated by energetic electrons trapped in a strong magnetic field. Damage to spacecraft electronics passing through the terrestrial radiation belts raised concerns about what could survive the higher fluxes at Jupiter suggested by the radio emissions.

Pioneer 10 and 11 were launched in 1972 and 1973, passed uneventfully through the asteroid belt and flew past Jupiter a year apart on November 27, 1972 and December 10, 1973, the first of several spacecraft to use Jupiter's gravity to get a boost to the outer solar system. Pioneer 10 passed 130,000 km above Jupiter's cloud tops measuring record fluxes of energetic ions and electrons, but with only minor electronic hiccups. So, Pioneer 11 was targeted even closer, 42,000 km above the clouds. Below we summarize the significant results:

• Images of Jupiter showed detailed cloud structure, particularly at boundaries between dark belts and light zones, hinting at convective motions but images were insufficient to allow tracking of features.

• Infrared emissions from Jupiter's nightside compared to the dayside, confirming that the planet radiates 1.9 times the heat received from the Sun with the poles being close to equatorial temperatures.

• Accurately tracking of the Doppler shift of the spacecraft's radio signal refined the gravitational field of Jupiter, constraining models of the deep interior.

• Similarly, the masses of the Galilean satellites were corrected by up to 10%, establishing a decline in their density with distance from Jupiter.

• Magnetic field measurements confirmed the strong magnetic field of Jupiter, putting tighter constraints on the higher order components.

• Occultation of Io by Pioneer 10 revealed a substantial ionosphere, indicative of a significant atmosphere.

• The magnetosphere of Jupiter was highly variable in size, extending up to 100 jovian radii.

• Detectors confirmed very high fluxes of energetic charged particles and that are absorbed by the satellites as they drift inwards towards Jupiter.

• Bursts of energetic particles are ejected from the jovian system and penetrate inwards as far as Earth.

Voyagers 1 & 2: Plotting the locations of the outer planets for the next 20 years showed that in the 1980s the planets would all be in the same quadrant of the solar system, providing a special opportunity to fly past all of the planets with a single spacecraft [4]. With a gravity-boost at each planet, a spacecraft would get to Neptune in 12 years instead of the minimum-energy flight time of 30 years. Thus, the planetary syzygy of the 1980s gave birth to the Grand Tour.

Voyagers 1 and 2 were launched in late summer 1977 and passed closest to Jupiter on March 5 and July 9, 1979. The spectacular pictures made headline news around the world. Movies of Jupiter's atmosphere showed turbulent eddies, dramatic wind shears, and clouds swirling around the Great Red Spot. Images of the Galilean moons revealed each to be a totally bizarre, different world - craters on Callisto, grooves on Ganymede, volcanic plumes on Io and mysterious lines across Europa. The preliminary scientific results were:

• Clouds of difference sizes move together due to bulk winds rather than wave motions, in a systematic zonal pattern, similar for both flybys.

• Clouds in the Great Red Spot exhibit anticyclonic motion with a period of about six days.

• The eddies or "spots" interact with each other, occasionally merging.

• Powerful lightning bolts penetrate the cloud tops.

• The upper atmosphere and ionosphere are hot.

• Ultraviolet observations indicate the presence of a high altitude absorbing haze in the polar regions.

• Strong ultraviolet and visible aurora circle Jupiter's magnetic poles.

• Voyager 1 observed eight active volcanoes on Io, with plumes extending 250 km above the surface. Voyager 2 found six were still active six months later.

• Spectral signatures indicate the presence of SO_2 as frost on the surface and gas in Io's atmosphere.

• Remarkably smooth surface of Europa, with few impact craters, intersecting linear cracks, indicates a geologically-young surface.

• Distinct cratered and grooved terrains on Ganymede suggest the ice-rich crust was once under tension.

• Callisto's heavily cratered ancient crust.

• First images of Amalthea reveal an elongated body with an irregular shape and reddish surface.

• A faint, narrow ring of material was detected.

• A million-amp electrical current flows along magnetic field lines linking Jupiter and Io.

• Strong ultraviolet emissions and in situ plasma measurements reveal a dense torus of electrons, sulfur and oxygen ions around Io's orbit.

Ulysses: To explore the high latitude solar wind, the ESA-NASA Ulysses mission used a Jupiter gravity assist to get the spacecraft's trajectory out of the ecliptic plane. The shape of the magnetosphere and structure of magnetic field measured on the pass through the high latitude dusk region suggests that the influence of the solar wind penetrates much deeper into Jupiter's giant magnetosphere than previously expected.

Galileo: The Galileo spacecraft was launched from Space Shuttle Atlantis on October 18th, 1989. After an extensive tour of the inner solar system, it reached Jupiter on December 7, 1995. Six months prior to arrival at Jupiter the probe was detached and allowed to free-fall into the planet. The 331 kg probe entered at 6.5° N latitude, sending data up to the orbiter for 60 minutes, by which time it had reached a depth of 22 bars, 150 km below the clouds. Galileo's main accomplishments are:

• The descent probe found the relative abundances of primary elements were different from the Sun.

• The atmosphere creates ammonia ice particles of material from lower depths, but only in fresh clouds.

• Lightning activity was definitively tied to large-scale moist convection of water clouds.

• Io's volcanic activity ~100 times greater than Earth.

• Plasma interactions with Io's atmosphere generates currents that couple to Jupiter's atmosphere.

• Ganymede is the first satellite known to possess an internally-generated magnetic field.

• Magnetic field perturbations show Europa, Ganymede and Callisto have hidden conductive oceans.

Cassini: The Cassini spacecraft passed Jupiter on its dusk side, just skimming inside the flank of the magnetosphere. The closest approach occurred on December 30, 2000 but remote sensing instruments took data for six months, while the Galileo spacecraft was inside Jupiter's magnetosphere and the Hubble Space Telescope observed the ultraviolet emissions from Jupiter's aurora. The main scientific results were:

• Similar to Voyager, the zonal wind profile with the east-west alternations were seen to extend to the poles.

• Observations of the rings at difference phases and wavelengths constrain the size distribution of particles.

• Spectral imaging of UV emissions from the Io plasma torus quantified spatial and temporal variations.

• Imaging of energetic neutral atoms showed energetic charged particles charge exchange with clouds of neutral atoms in the vicinity of Io and Europa.

Juno: The Juno spacecraft has been in orbit around Jupiter since July 2016, completing 17 pole-to-pole passes to date. It is the first spacecraft to view the polar atmosphere and sample the particles and fields of the auroral regions. Juno is mapping out the gravity and magnetic fields as well as measuring the microwave emission from the hot interior below the clouds. The main scientific results are:

• The magnetic field shows detailed structure with stronger, more irregular fields in the north [5].

• Gravity measurements reveal the heavy elements in the core are mixed with the liquid metallic hydrogen, spreading to 40% of Jupiter's radius [6].

• Microwave measurements show atmospheric convection extends down to ~3000 km [7].

• Systems of polar cyclones (5 south, 8 north) persist for over 2.5 years of mission to date [8].

• Intense aurora are excited by powerful beams of charged particles that are driven by stochastic processes rather than steady electric potentials at Earth [9].

A major success of Juno is the camera (JunoCam [10]), included as an outreach instrument, which produces spectacular images that are processed by citizen scientists and artists.

Future missions Europa Clipper and JUICE will explore the jovian system, focusing on Galilean moons.

References: [1] Bagenal F., Dowling T. E. and McKinnon W. B. (2004) *Jupiter: Planet, Satellites, Magnetosphere*, CUP [2] Bolton S. J. et al. (2017) *Science* 356, 821-825 [3] Burke B.F. and Franklin K.L. (1955) *JGR*, 60, 213-217 [4] Flandro G. (1966) *Astronaut. Acta* 12 [5] Connerney J.E.P. et al. (2018) *JGR*, 45 [6] Wahl, S.M. et al. (2017) *GRL*, 44, 4649–4659 [7] Kaspi, Y. et al. (2018) *Nature*, 25793 [8] Adriani, A. et al. (2017) *Nature*, 25491 [9] Mauk, B.H. et al. (2017) *Nature,* 549, 23648 [10] Hansen, C.J. et al. (2017) *Space Sci. Rev.*, 213, 475-506