

MULTIPLE DEEP JOVIAN ATMOSPHERIC ENTRY PROBES: BUILDING ON THE GALILEO PROBE

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Submitted to Planetary and Space Science, for inclusion in the Nantes '98 special
issue, August 31, 1998

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ABSTRACT

Following on the very successful Galileo Entry Probe mission, studies underway at the Jet Propulsion Laboratory (JPL) address the feasibility and cost of the "Jupiter Deep Multi-probes" (JDMP) mission to deliver and support multiple deep (100 bar level or deeper) atmospheric entry probes to Jupiter. In 1997 the Astrophysical Analogs in the Solar System Campaign Science Working Group (AACSWG), advising NASA's Solar System Exploration Subcommittee (SSES), gave the JDMP mission its highest priority for near-term giant planet missions. They generated a list of the highest-priority science and measurement objectives to guide the JDMP mission studies. These feasibility studies examine options for implementation of the probes themselves, support, and delivery. Results suggest that with moderate technology development funding, probes with masses about a quarter that of the Galileo Probe are possible, with instrument capabilities comparable to or better than Galileo Probe analogs. These studies examine a large range of delivery options, including a dedicated carrier/relay spacecraft (CRSC) and delivery by other spacecraft. Dedicated CRSC delivery options range from purely chemical direct and gravity-assist trajectories, to various SEP options. Potential "other spacecraft" include those from all near-term planned NASA missions with Jupiter in their itineraries, such as Pluto/Kuiper Express, Solar Probe, and Europa Orbiter.

I. INTRODUCTION

The successful completion of the Galileo atmospheric entry probe's mission into Jupiter's upper and middle troposphere delighted the planetary science community. In some cases, its findings supported the results of previous indirect studies, and in some it provided fundamentally new data, but in others it pointed to the shortfalls in our knowledge of the jovian atmosphere. Among the lessons learned from that mission are that our fundamental understanding of Jupiter's atmospheric dynamics was not as accurate as thought, that single entry probes are not the best means for characterizing a dynamic, spatially and temporally variable atmosphere, and that sampling down to the 20 bar level is not sufficient to resolve some of the modeling difficulties. Where many models had predicted that zonal flow speeds would peak somewhere in the 2 to 5 bar range, the Galileo results indicate that they were still accelerating slightly with depth at the deepest levels sampled, below the 20 bar level; energy flowing from the interior seems to play a more important role than anticipated. The probe's entry into what has been described as a "3- σ hot spot" emphasizes a possible pitfall for single entry probes: inadvertently sampling a region that is decidedly non-representative of the atmosphere's general characteristics. While clouds at levels above the 5 bar level are abundant over most of Jupiter's disk, the Galileo probe found only thin wisps of clouds, including the ammonia cloud. And the Galileo probe apparently did not penetrate sufficiently deeply to measure fundamental parameters of the planet's atmospheric dynamics and deep interior. In addition to not reaching depths of decreasing zonal wind speeds, the measured mixing ratios of H₂O, H₂S, and NH₃ were still increasing with depth at the deepest datum.

To understand Jupiter's atmospheric structure, dynamics, and deep constituent abundances and their implications for planetary and solar system origins, deeper *in situ* probes are needed. Multiple probes are needed to avoid the biased-sample problem experienced by Galileo, and to address questions of spatial variability. In 1997 the Astrophysical Analogs in the Solar System Campaign Science Working Group (AACSWG) assigned its top priority to a mission to deliver such probes to Jupiter. Since mid-1995 the AACSWG and its predecessor, the Outer Planets Science Working Group, have guided studies of Jupiter probe missions performed by JPL's Advanced Projects Design Team, "Team X." Results from the Galileo entry probe mission steered those studies toward multiple deep probes. This paper describes the science objectives addressed by the mission as envisioned in the most recent (Nov. 1997) Team X study (Bennett et al., 1997), and their relationships to the Solar System Exploration Roadmap (SSER). It also discusses various aspects of the mission implementation, including a trajectory design concept that significantly reduces the total mission cost as compared to previous designs.

II. SCIENCE OBJECTIVES

The Jupiter Deep Multiprobes (JDMP) mission's four primary science goals are to understand:

1. Jupiter's bulk composition and compositional gradients, especially as they relate to solar system formation and planetary evolution
2. Jupiter's atmospheric chemistry
3. Jupiter's atmospheric structure and dynamics
4. Spatial variability in Jupiter's troposphere and deeper

These goals are supported by the mission's measurement objectives, in rough priority order:

1. Mixing ratios of the primary bearers of C, O, N, and S, as a function of depth
2. Cloud characteristics (composition, density, particle size)
3. Atmospheric structure: temperature, pressure, and density as a function of depth
4. Bulk flow velocity (wind) as a function of depth
5. Vertical radiant energy flux as a function of depth
6. Ortho- to para-H₂ ratio
7. Noble gas and disequilibrium species mixing ratios as a function of depth; isotopic ratios for selected elements

Note that even the last of these objectives is a high priority item on a list of *all possible* useful observations. Measuring the bulk helium abundance, formerly a high-priority objective, is absent from the list above, since the Galileo probe appears to have performed that task adequately. Examples of species targetted in Objective 1 would include CH₄, H₂O, H₂S, NH₃, and N₂ if possible. Objective 7 might target such species as Ar, Kr, and Xe for the noble gases, and CO, PH₃, AsH₃, and GeH₄ for the disequilibrium species. Where possible the measurements are to be made over an altitude range from the 0.1 bar level to the 100 bar level, with a vertical sampling rate of six or more samples per atmospheric scale height (~20-25 km in Jupiter's troposphere). Practical telemetry rate limitations degrade that resolution at the deepest levels. Below the 20 bar level, Objectives 3, 4, and the disequilibrium species part of Objective 7 have the highest priorities.

III. ROLE IN NASA'S SOLAR SYSTEM EXPLORATION ROADMAP

The objectives listed above address all three of the major topics of the SSER "Quest," *To Explain the Formation and Evolution of the Solar System and Earth*:

1. Solar System Origin and Planet Formation
 - Physical and chemical records: Primitive bodies and giant planets
2. Evolutionary Processes and Diversity
 - Atmosphere formation, dynamics, and surface interactions
3. A Natural Science Lab
 - Large-scale atmospheric phenomena

It bridges two of the five principal SSER Campaigns:

1. Building Blocks and Our Chemical Origins
2. Astrophysical Analogs in the Solar System

By mutual agreement of those two campaign's SWGs, the AACSWG has primary responsibility for the JDMP mission. As previously mentioned, the AACSWG made the JDMP mission its highest priority for near-term missions. NASA now lists it in their Strategic Plan.

IV. CANDIDATE INSTRUMENT COMPLEMENT

Mission measurement objectives are met by a suite of six instruments:

1. Gas Chromatograph / Mass Spectrometer (GCMS)
2. Atmospheric Structure Instrument package (ASI), consisting of thermometers, pressure transducers, and accelerometers
3. Nephelometer (NI)
4. Net Flux Radiometer (NFR)
5. Acoustic Velocity Instrument (AVI), for ortho- to para-H₂ ratios
6. Ultrastable Oscillator (USO) for Doppler Wind experiments

Table 1 shows the mapping of the measurement objectives onto the instruments. The GCMS is a change from previous public discussions of the JDMP mission. A study at JPL this year, led by G.E. Danielson, concluded that a GCMS was more appropriate for the measurements desired, and could meet the measurement requirements with less money spent on technology development than a neutral mass spectrometer. That study outlined GCMS data compression techniques that significantly reduce demands on the spacecraft's telecom system, allowing reductions in telecom system mass. Analysis by D.H. Atkinson indicates that the ASI's accelerometers are insufficient for deep wind speed measurements (Atkinson, 1998, private communication). A Doppler Wind experiment performs those measurements, so each probe carries an Ultrastable Oscillator (USO).

The Galileo entry probe's instrument complement included earlier versions of all the JDMP instruments. Reflying them speaks to the variability of the jovian atmosphere, not to failures of any Galileo probe investigations. Most of these instruments are miniaturized versions of their Galileo counterparts and require significant development effort.

V. MISSION DESIGN

The AACSWG has determined that the JDMP mission should sample three different latitudes in the jovian atmosphere: one closely equatorial, one at $\sim 25^\circ$ N, and one at $\sim 25^\circ$ S, targeting a mix of zones and belts. Previous mission designs attempting to implement such latitude sampling generated expensive missions. One concept required placing in orbit around Jupiter the Carrier/Relay Spacecraft (CRSC), the spacecraft that delivers the entry probes to their entry trajectories and then receives and relays their data to Earth. Others could sample latitudes only up to $\pm 10^\circ$, or required multiple probe data receivers and multiple gimballed probe data reception antennas. A mission design conceived last year at JPL avoids the expense and added complexity of placing the CRSC in jovian orbit, yet allows independent targeting of up to four probes at four different latitudes in the range $\pm 25^\circ$, with a single probe data receiver fed by the same high gain antenna (HGA) used for the CRSC-to-Earth data link. The current baseline mission design implements that with AACSWG's three-probe mission.

The new mission design, illustrated in Figure 1, hinges on taking most of the trajectories significantly out of the jovian equatorial plane and separating them temporally. The CRSC itself performs a flyby at a very nearly polar inclination. About six months prior to that flyby the CRSC, with its full complement of entry probes, is on the South Probe (SP) approach trajectory, the red one in Figure 1; were it to continue on this trajectory, it would enter along with the SP at $\sim 25^\circ$ S latitude. That probe is released and continues unguided on that trajectory until its precisely timed entry some six months later. The Galileo Probe demonstrated this delivery technique, except that the SP trajectory is inclined $45\text{-}60^\circ$ to the jovian equatorial plane. Following release of the SP, the CRSC performs a ΔV maneuver of 40 to 70 m/s (depending on the precise latitude targets and approach trajectory inclinations) that places it on the Equatorial Probe (EP) trajectory, the green one in Figure 1, very similar to the Galileo Probe trajectory. When the trajectory's accuracy is confirmed, the EP is released. This trajectory is timed such that the EP arrives at its entry point

about two hours before the SP reaches its entry point. Although nearly equatorial, this trajectory should be inclined slightly to avoid the densest parts of Jupiter's dust ring. After releasing the EP, another CRSC ΔV maneuver places it and the remaining North Probe (NP) on the NP trajectory, the blue one in Figure 1. It is timed to enter at $\sim 25^\circ$ N latitude about two hours before the EP enters. The NP is released, and then a final ΔV maneuver of similar magnitude places the CRSC on its final trajectory, shown by the wide black line in Figure 1. Its timing places the CRSC $45\text{--}50^\circ$ north of the equatorial plane as the NP, the first of the trio, arrives at its entry point. This enables the data relay strategy illustrated in Figure 2.

The sequential entries of the three probes, along with the near-polar north to south CRSC flyby, result in three sequential data link windows of 1.5-2 hours duration each. Each is serviced by a UHF (or possibly L-band) feed on the CRSC's HGA. Actual link durations are limited primarily by Jupiter's rotation rate, the fastest of the solar system's planets and faster than the CRSC's joviocentric angular rate.

The November 1997 Team X study included updating the probe designs based on new information about useful technologies, and delivery of the redesigned probes by other spacecraft with Jupiter in their itineraries, on a one-at-a-time basis. These "other spacecraft" are the three missions in NASA's Outer Planets and Solar Probe Program. Since that study, programmatic changes have left only the Solar Probe mission design intact; the Europa Orbiter and Pluto Express mission designs have changed significantly.

At the time of the study the baseline Pluto Express mission design featured a 2003 launch and a prograde, equatorial jovian gravity assist flyby with a 4-6 R_J perijove, very nearly optimal for delivering a single probe. The science return from a probe delivered by that mission is even greater than from any single probe of the Dedicated CRSC mission, due to a longer link window duration. But plans now call for a December 2004 launch with a much larger perijove distance, significantly decreasing the total data volume attainable.

Also at that time the Europa Orbiter mission design called for a Jupiter Orbit Insertion maneuver at a very small distance, only 1.02 R_J . This yields a link window duration of only 4 minutes near periapse unless the orbiter carries the probes into orbit. Both cases are untenable given the already severe demands of a Europa Orbiter mission, so delivery by this mission was not given further consideration. Since then the mission design has moved to much larger perijove distances, $\sim 3 R_J$, far more attractive for probe delivery. Unfortunately mission designers for that mission do not anticipate having the 100 kg unallocated mass margin needed to accommodate a single probe.

Solar Probe's mission design is the most stable, but is also the least attractive due to its retrograde gravity assist flyby. Figure 3 illustrates the Solar Probe flyby geometry and the resulting best-case probe entry and relay geometries. An entry probe released from Solar Probe on a prograde trajectory (requiring significant additional ΔV for Solar Probe to move to its proper trajectory) enters Jupiter's atmosphere $\sim 18^\circ$ behind the terminator, so sunlight extinction measurements are lost. Solar Probe's perijove radius, $\sim 10 R_J$, occurs out of sight of the probe, so the probe's entry must be timed significantly after perijove passage, when Solar Probe is at $\sim 15 R_J$ and receding. Solar Probe's retrograde motion yields a short link window duration, less than one hour, and its large joviocentric distance during data relay yields low data rates.

VI. PROBE DESCENT DURATION

The Galileo entry probe, under a moderately sized parachute, made its descent from the 0.1 bar level to 20 bars in slightly less than one hour. The JDMP probes must descend to 100 bars through a much denser medium, so descent time is a concern. Assuming subsonic, turbulent flow drag conditions, a descent module of reasonable size (35 kg, with a $C_D A$ of 0.14 m^2), and the Orton III atmosphere, descent profiles were calculated for three cases: no parachute for the entire descent; a small parachute for the entire descent; and a small parachute carried to the 20 bar level and then released. Figure 4 gives the results of those calculations. Even with a small parachute,

descents entirely under a parachute are too lengthy. But it also shows there are multiple combinations of parachute sizes and release altitudes that can produce descent durations as short as one hour. The baselined mission design allows longer descents.

VII. DATA RELAY

Using the CRSC HGA for probe communications yields higher performance than Galileo achieved with its Medium Gain Antenna. Distances are similar to Galileo's, but even with a smaller transmitter than Galileo transfer rates of 250 bps are possible in the early stages of descent. As the probe descends, absorption of the microwave signal first by NH_3 , and later by NH_3 , H_2O , and possibly by cloud droplets, attenuates the signal, forcing a decrease in the bit rate. Using software written for this purpose based on the ammonia absorption formalism by Spilker (1990, 1993) and the water absorption formalism by Goodman (1969) modified by more recent results by Liebe et al. (1987), estimates of the microwave opacity profile were calculated for three different candidate radio frequencies. These calculations neglect absorption by water droplets, but given the uncertainties in droplet sizes in jovian clouds, droplet conductivities due to dissolved polar species, etc., water droplet absorption calculations are highly speculative at best. In a cosmic Catch-22 situation, reliable knowledge of this phenomenon in Jupiter's atmosphere must wait for entry probe missions. Figure 5 shows the results of the opacity calculations, based on solar ammonia and water abundances.

Using UHF frequencies, the 250 bps rate can be maintained to about the 20 bar level. Assuming a single data rate change, it must then drop to ~50 bps to allow maintaining the link to 100 bars. For a typical descent profile, this yields 300-400 kbits of data from 0.1 to 20 bars, and then 60-90 kbits from below the 20 bar level. The lower data rate will not nearly support six samples per scale height. Unless lossy data compression schemes are used, only two or three full samples of GCMS data are obtained below the 20 bars. Reasonable lossy data compression schemes might increase that by a factor of three.

Recent results using the Galileo probe's relay link system performance indicate that the deep ammonia abundance may be more than three times solar (Folkner, Woo, and Nandi, 1998). If this is confirmed, the opacity profiles must be recalculated and the relay telecom system redesigned.

VIII. RADIATION

Jupiter's intense radiation belts, consisting mostly of protons and electrons trapped in the powerful magnetic field and accelerated to energies up to 100 MeV, present a significant hazard to spacecraft operating in Jupiter's vicinity. The structure and intensity of those belts are illustrated in Figure 6, which shows a cross section of the toroidal belts, based on measurements made by the Pioneer 10 and 11 spacecraft (Van Allen, 1976). Fortunately, the CRSC for this mission absorbs a relatively low integrated dose compared to past and other planned missions. The Galileo orbiter spacecraft was designed for a total lifetime fluence of 150 krad, half of which was expected during its first pass by Jupiter, where it approached in the equatorial plane, encountered Io, continued inward to ~4 R_J , and then remained in the equatorial plane as it performed its orbit insertion maneuver and exited toward apojoove. Such an equatorial trajectory results in high fluences. The spacecraft spent tens of R_J of pathlength (and thus much time) within the region bounded by the outer flux contour. Since perijove was near 4 R_J , the trajectory was nearly tangent to the innermost contour, contributing greatly to the total fluence. But the CRSC for the JDMP mission approaches at very high inclination, spending only ~6 R_J of pathlength within the outer contour. Anticipated total fluence is less than 1/3 of the Galileo orbiter's fluence for the first perijove pass, or less than 30 krad. Contrasting this with the anticipated fluence for the Europa Orbiter mission concept currently under study, nearly 4 Mrad, the CRSC's radiation environment is relatively benign. Since it approaches to ~4 or 5 R_J in the equatorial plane, the CRSC's worst-case single event upset environment will be similar to Galileo's. This should not present any significant problems.

IX. MISSION COST

Before this mission becomes an approved project, ~\$15M must be allocated for technology development unless it waits for development elsewhere. This includes development of miniaturized instruments, notably the GCMS, and various spacecraft subsystem improvements. Given these developments, the end-to-end cost for the entire mission is estimated at \$350M, including all post-launch operations and a Delta III launch vehicle. This is a significant decrease from initial estimates (not using the new mission design) that were \$450-500M. It might be possible to further decrease the mission cost by reducing the number of probes, but this significantly impacts the science objectives, especially spatial variability. Delivery of single probes via other spacecraft already targeted at Jupiter, such as Europa Orbiter, Solar Probe, or Pluto Express, adds ~\$100M to the cost of the delivering missions, but would lose the quasi-simultaneity of the Dedicated CRSC mission. Studies indicate that given the technology development programs mentioned above, a single-probe mission delivered by a Delta 7925H and a dedicated CRSC would be viable as a NASA Discovery Program mission.

X. ACKNOWLEDGEMENT

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract from the United States of America's National Aeronautics and Space Administration.

XI. REFERENCES

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Table and Figure Captions

Table Captions

Table 1: Mapping the measurement objectives to the instrument complement

Figure Captions

Figure 1: Mission design for a mission using a single Carrier/Relay Spacecraft (CRSC) that delivers and supports three jovian atmospheric entry probes, without entering jovian orbit

Figure 2: Relay time allocation strategy for the mission illustrated in Figure 1

Figure 3: Mission design and data relay strategy for delivery of a single jovian atmospheric entry probe by the Solar Probe spacecraft

Figure 4: Descent time profiles for various descent-slowing strategies. The blue curve shows a representative profile for a probe descending without a parachute. The black curve shows a profile for an identical probe that deploys a parachute at the 0.1 bar level and retains it for the entire duration of the descent to the 100 bar level. The red curve shows the profile for an identical probe that deploys the parachute at the 0.1 bar level, but releases it at the 20 bar level for a faster descent. Above the 20 bar level (to the left of the "20 bar level" line on the graph) the red and black curves are identical.

Figure 5: Integrated vertical radio opacity profiles for the jovian atmosphere for three candidate data relay frequencies. Solar abundances of water and ammonia vapors are assumed.

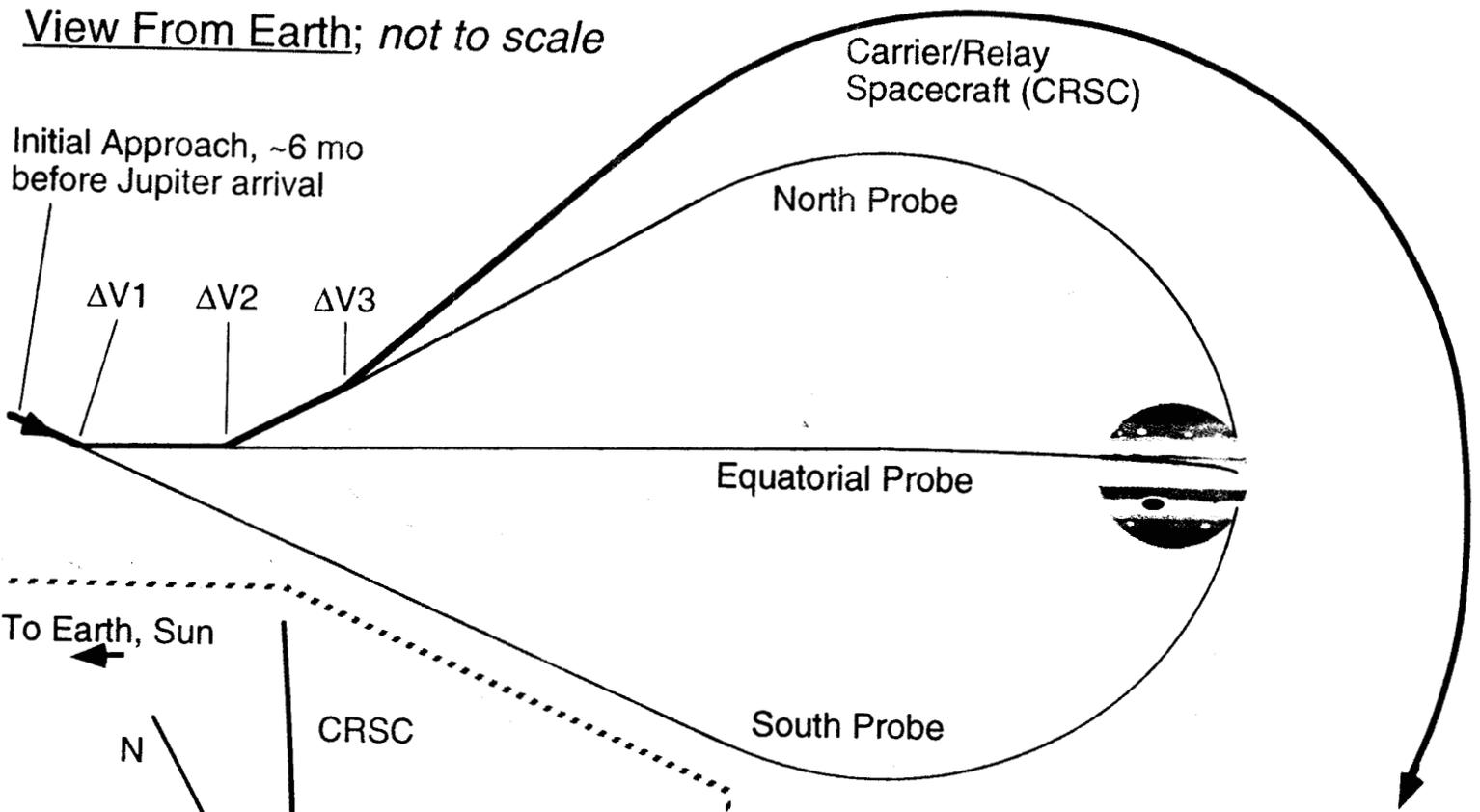
Figure 6: Illustration of Jupiter's radiation belts, with the CRSC trajectory

Instrument ->	GCMS	ASI	NI	NFR	AVI	USO
<u>Measurements</u>						
C-O-N-S bearer Mixing Ratios	X					
Atmospheric Structure		X				
Wind Speeds		X				X
Cloud Properties			X			
Vertical Energy Flux				X		
Ortho- to Para- H ₂ ratio					X	
Noble Gases et al. Mixing Ratios	X					

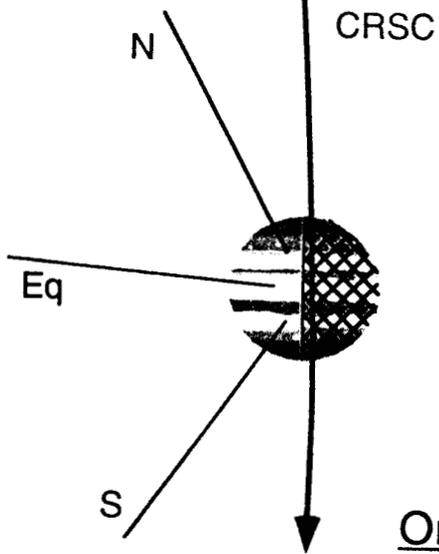
Spilker & Hubbard, Table 1

View From Earth; not to scale

Initial Approach, ~6 mo before Jupiter arrival



To Earth, Sun



Orthogonal view

ΔV s shown are 40-70 m/s each

View From Ecliptic North

