PROSPECTS FOR THE VOYAGER EXTRA-PLANETARY AND INTERSTELLAR MISSION*

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An advance study has been conducted to examine the trajectory characteristics of Voyager 1 and 2 as they depart from the Solar System and traverse interstellar space. A survey of the extraplanetary phase, commencing with completion of the final planetary encounters and ceasing with loss of spacecraft communication, considers the trajectory aspects attendant to a heliospheric investigation and possible sensing of a trans-Neptunian massive body. An analysis of departure telecommunications capability attempts to bound the inevitable time of communication loss. A study of the interstellar phase examines closest approaches of the spacecraft to the Sun's stellar neighbours. A covariance analysis is provided to illustrate the statistical effect of stellar state uncertainties on these approaches. In addition to the Voyager spacecraft, data for Pioneers 10 and 11 are provided where appropriate.

1. INTRODUCTION

The prime mission of the Voyager spacecraft ended in late 1981 after the Voyager 2 flyby of the planet Saturn. Since that time the Voyagers have entered into an extended mission phase, the highlights of which will be the Voyager 2 encounters of Uranus (January 1986) and Neptune (August 1989). Beyond these events, it is reasonable to expect that these spacecraft will remain healthy and in communication with flight controllers on Earth. It is both natural and necessary to consider what could then be done with these craft to carry on their missions of scientific inquiry. Furthermore, the Voyager flight team, by virtue of having launched this hardware into interstellar space, incurs a responsibility for documenting its eventual disposition, within the limits of current knowledge.

This paper will seek to provide up-to-date trajectory data pertaining to the extra-planetary and interstellar phases of the Voyager flight paths. Along with strictly geometric data, analyses will be provided concerning specific science investigations, directly related to departure trajectory parameters, which may be conducted while the spacecraft are still in communication with Earth. An analysis of the eventual 'destinations' of the spacecraft will also be provided.

The 'near' extra-planetary phase of the mission is treated first. This phase begins when the Voyagers complete their intended planetary encounters (already completed for Voyager 1), and ends when spacecraft-Earth communication should be lost. Investigation of the heliosphere, the region of our Sun's magnetic influence, embedded in the surrounding interstellar medium (ISM), will be one of the prime scientific objectives during this mission phase.

An additional investigation during this phase may involve an effort to detect previously unknown sources of gravitational perturbation on the spacecraft trajectories. If detectable at all, these perturbations would likely appear as slight unmodelled accelerations persisting in spacecraft orbit reconstructions. Possible sources for these perturbations could include unknown Solar System bodies and/or interstellar wanderers. Analysis of the near extra-planetary phase concludes with an examination of possible reasons for loss of communication with the Voyagers. This analysis will examine telecommunications performance, thermoelectric power supply decline and attitude control propellant depletion in order to estimate the time of occurrance of this inevitable event.

The near-stellar phase of the mission is treated next, including an analysis of the trajectories of the spacecraft through the local group of 'nearby' stars. Close approaches of the Sun's stellar neighbours by the Voyagers are examined. Range time histories are provided for some of the more favourable stellar flybys. For Voyager 1 there are no further planetary encounters, and hence no gravity assist opportunities to provide trajectory shaping for stellar flybys. The onboard propellant supply is insufficient to effect much change. For Voyager 2 however, the choice of aimpoint for the upcoming Neptune flyby, which will be driven by Neptune science considerations, can nevertheless make substantial alterations in the spacecraft's Solar System departure velocity, yielding different trajectories through the local stellar group. In addition to this analysis which is deterministic, a rudimentary covariance analysis will also be provided for both Voyagers, in order to obtain statistical estimates of stellar flyby trajectory parameters.

In addition to the Voyager spacecraft, relevant data for Pioneers 10 and 11, which are also escaping the Solar System ahead of the Voyagers although at a slower velocity, will be provided, where appropriate.

2. NEAR EXTRA-PLANETARY PHASE

2.1 Voyager Heliospheric Mission

Thanks to their gravity-assist flybys of Jupiter in 1979, the twin Voyager spacecraft have attained hyperbolic conditions well in excess of Solar System escape energy, and are thus destined to leave the system forever. Subsequent encounters with Saturn, as well as the Voyager 2 flybys of Uranus and Neptune, all occur on the outbound legs of the two respective trajectories, as shown in the ecliptic plane projection of Fig. 1. The flight paths of Pioneers 10 and 11, the Voyager predecessors, are shown in the same figure. For each spacecraft the directions of the heliocentric escape

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* The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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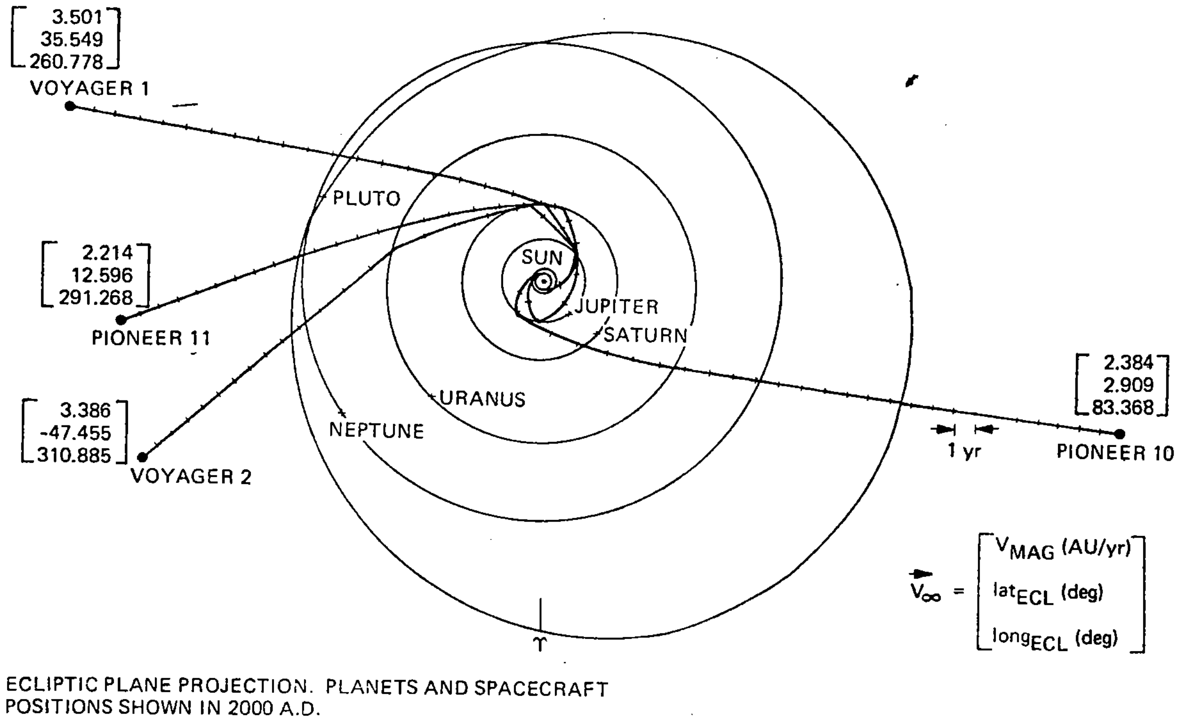

Fig. 1. Ecliptic plane projection of the first four Solar System escaping spacecraft trajectories. Planets and spacecraft positions shown in 2000 A.D.

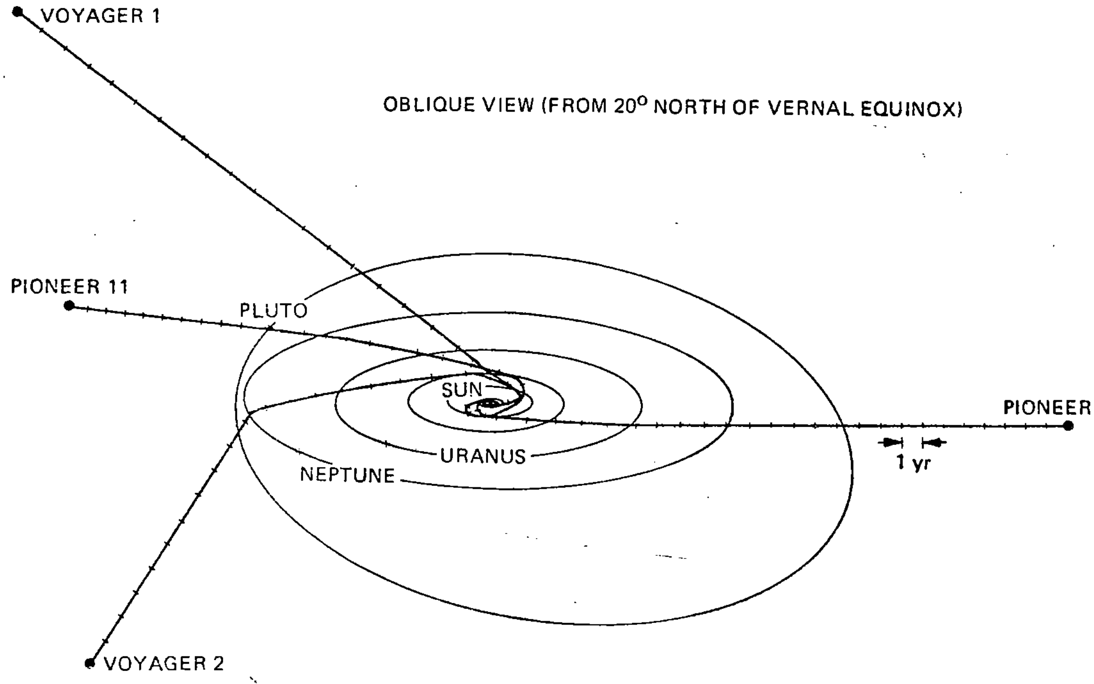

Fig. 2. Oblique view (from 20° north of Vernal Equinox) of Solar System escaping spacecraft trajectories. Planets and spacecraft positions shown in 2000 A.D.

asymptotes (with respect to the ecliptic of 1950) and the departure V_∞ magnitudes, in AU/year (1 AU = 149,600,000 km), are indicated on the plot. As can be seen in an oblique view of the same four trajectories (Fig. 2), Voyager 1 is rising steeply out of and above the ecliptic plane at a 35.5 degree angle, while the current nominal Voyager 2 Neptune flyby option trajectory descends, even more steeply, below the ecliptic at -47.5 degrees. For Pioneers 10 and 11, the heliocentric departure asymptotes lie much closer to the ecliptic: 2.9 and 12.6 degrees, respectively. The velocities with which these first interstellar probes are leaving the system are about 3.5 AU/year for the Voyagers and 2.5 AU/year for the Pioneers.

As these spacecraft race toward interstellar (I/S) space, they will traverse distant reaches of the Solar System, occupied by solar wind particles, mostly protons, ejected by the Sun and speeding radially out at about 450 km/sec. This wind is variable in speed by a factor of about two; it

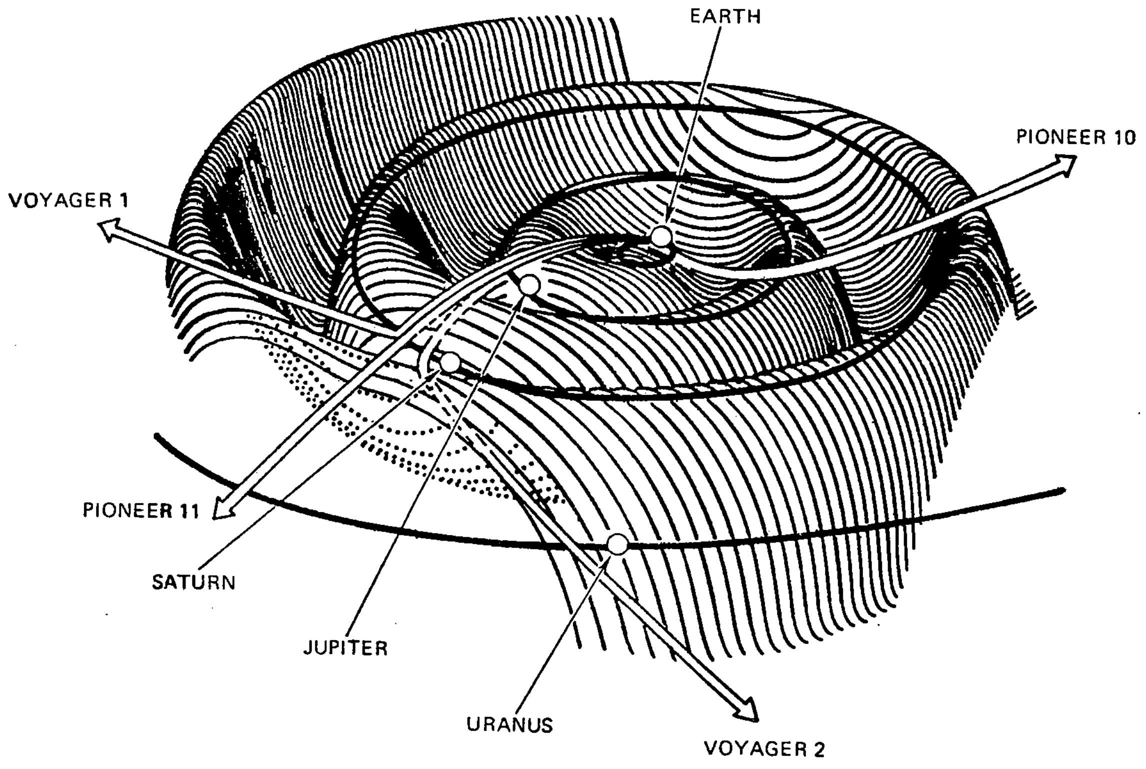

Fig. 3. Spiral Solar current sheet shown out to 20 AU; Spacecraft observe magnetic field polarity reversal at current sheet crossings.

carries outward with it the solar magnetic field lines, which now form a flat spiral pattern corotating with the Sun. A thin, wavy charged particle current sheet is formed along the solar equator, which is inclined at 7 degrees to the ecliptic. Its waviness, composed of alternating crests and valleys, also forms a spiral pattern. This is caused by a tilt of the solar magnetic field axis to the Sun's rotation (equator) pole, amounting on the average to about 15 degrees (see Fig. 3). The current, flowing in this sheet, starts out azimuthally (i.e. in a circle), but gradually its direction steepens and it eventually becomes radial, at right angles to the Archimedian spiral of the interplanetary magnetic field lines.

The region of space surrounding the Sun, where all these events are taking place, forms a magnetic bubble, called the heliosphere. It is inflated by the solar wind: its boundary, the heliopause, is formed at distances corresponding to dynamic pressure equilibrium with the interstellar medium (ISM). In its motion around the Galaxy, the Sun's heliosphere rams its way through the ISM – a tenuous gas composed mostly of neutral hydrogen and helium. The ISM varies greatly in density, direction and velocity of galactic motion. It is quite probable that the heliopause distance fluctuates in response to prevailing ISM and solar wind conditions. Solar magnetic field lines, the return paths of the electric current sheet and the trajectories of the solar wind particles are all thought to be constrained by the heliopause boundary.

A typical model of the hypothetical interaction region between the solar wind and the ISM is shown in Fig. 4. It may be quite complex. This model, discussed by Smith [1, 2], envisions an upstream shock front at which the 450 km/s supersonic radial flow of solar wind protons decelerates to a subsonic speed. In the heliosheath – the turbulent region between this shock and the heliopause boundary - the spiraling magnetic field lines are turned about, while the radial flow of the solar wind now begins to be deflected downstream, along the inner wall of the heliopause towards its tail. Currently the thickness of the heliosheath is assumed to be about 40 AU.

Upstream of the heliopause, in the ISM, a bow shock is to be expected, at which the incoming 'interstellar wind' (ISW) receives its first warning of impending collision with our star's magnetosphere. Downstream from the Sun along the ISW, on the other hand, a long turbulent tail, in general similar to a planetary magnetotail, is anticipated. The extent to which interstellar material is penetrating inside the heliopause, while exchanging charges and mixing with the decelerated solar wind, is open to question. The result of such an interaction would manifest itself in a strong Lyman-α ultraviolet glow from the upstream direction. Indeed this L_α glow was detected more than a decade ago and was subsequently observed by a variety of spacecraft. This L_α radiation has pinpointed the direction "into the ISW" as $(\alpha_{50}, \delta_{50}) = (252.0°, -15.0°)$ and $(\ell, b) = (4.5°, 18.2°)$, in EME50 and galactic coordinates, respectively [3]. The estimated Sun-relative velocity of the ISW is about -20 km/s.

The direction and magnitude of the ISW velocity are the resultant of vectorial addition of the basic solar motion and the interstellar medium's bulk velocity with respect to the Local System of Rest (LSR) defined (e.g., Mihalas [4]) by averaging motions in the stellar neighbourhood of the Sun. These motions are highly complex.

On a much larger scale, necessary to be considered in order to properly understand local ISM phenomena, the general *retrograde* motion of galactic plane objects is near-circular and differential, but it is not Keplerian. Our Sun presently orbits the Galaxy at a distance of 8.2 kpc (1 kiloparsec = 1000 parsec, 1 pc = 3.26 light years = 206,000 AU) with a period of about 245 million years. Its orbit, however, is thought to resemble an epicycle, since it is affected by a host of minor perturbations resulting from local stellar and gas cloud gravitational attractions. The velocity dispersions

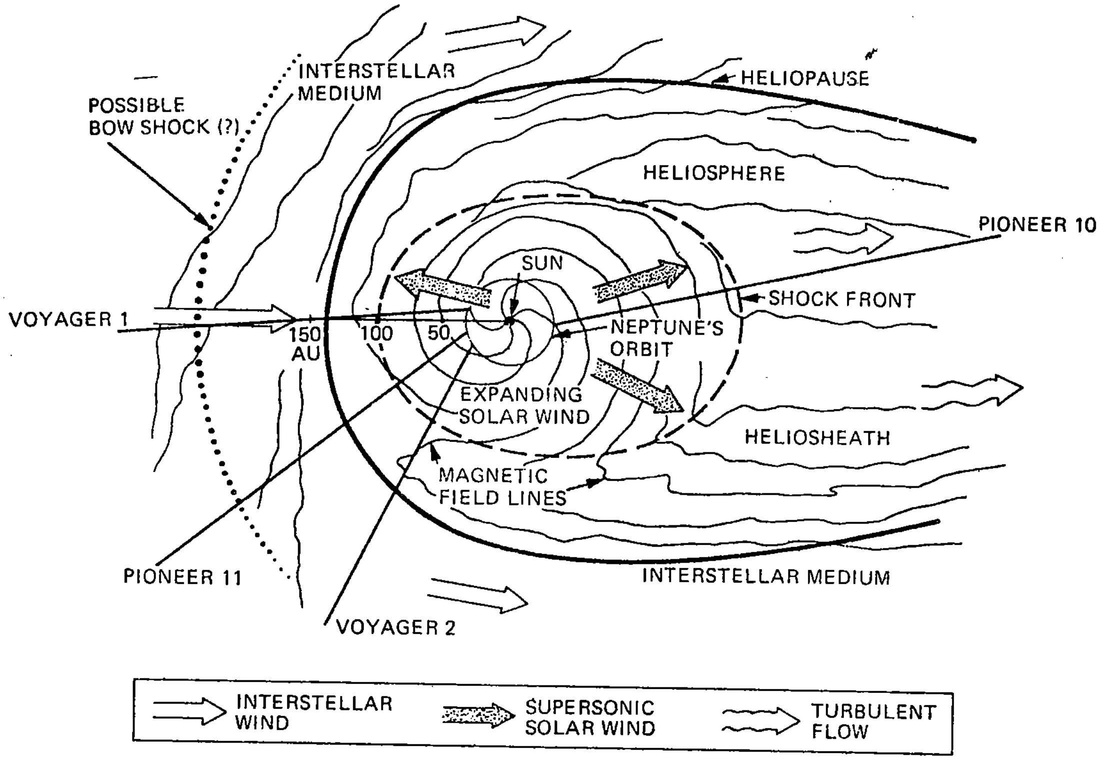

Fig. 4. Hypothetical Heliosphere model, projected into Solar equator plane (after E. J. Smith [2]) and showing trajectories of Solar System escaping spacecraft.

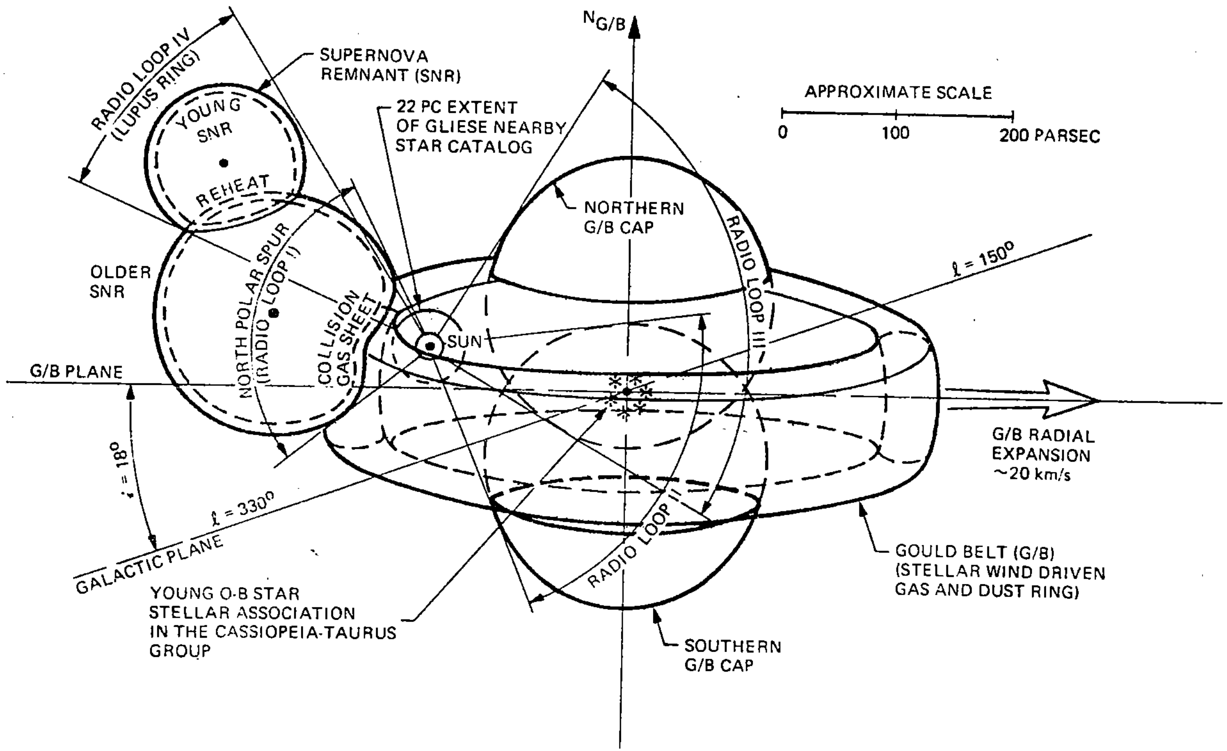

Fig. 5. Schematic of local Interstellar Medium, showing Sun and hypothetical interaction of two supernova remnants with Gould Belt; view normal to plane containing ℓ = 330/150-deg galactic meridian.

of these nearby stars were originally inherited from proto-stellar cloud motions before the particular stars formed. Cloud motion dispersions themselves are set by supernova explosions, strong stellar winds from massive young O-B stars and possibly by galactic spiral-density-wave shock-front related phenomena.

The expansion of supernova remnants (SNR) and strong stellar winds are particularly effective in sweeping up interstellar gas and dust and incorporating it into ever expanding spherical shells and rings. The creation of young stars is crucially dependent on this 'snowplow' accumulation of material to the point of causing the gravitational collapse of a cloud fragment unto itself. On the scale of 1 kpc the larger neighbourhood of our Sun is a typical network of mutually intersecting SNR cloud shells. Figure 5, based on a combination of models published by Iwan [5] and Olano [6] illustrates the possible collision geometry of nearby gigantic gaseous structures, as revealed by radio-astronomy and X-ray measurements in the Local Interstellar Medium (LISM).

Collisions of SNR shells amongst themselves or with cold gas cause more shocks and result in a violent reheat of these gaseous structures. On a smaller scale, local fragments of these clouds do partake in the turbulent LISM motion. According to a general model developed by McKee and Ostriker [7], interstellar gas clouds vary greatly in size (200 pc to 0.01 pc) and makeup. They consist of three essential components, the coldest and densest of these is the Cold Neutral Medium ('CNM'), found at the central cores of dense dark clouds. Its temperature is as low as 80°K, its density typically 10 to 40 (or more) atoms/cm^3. These cores are surrounded by a shell of 'WNM' (Warm Neutral Medium), typically of $T = 8000°K$ and 0.4 atoms/cm^3. An outer layer of 'WIM' (Warm Ionised Medium) covers the typical cloud; its excited state is attributable to UV light from neighbouring stars. All of these clouds, on the average 2 pc in size, on the order of 10 pc apart, float in a sea of rarefied Hot Ionised Intercloud Medium ('HIM'), typically 500,000°K and 0.003 atoms/cm^3. The immediate neighbourhood of the Sun is composed of 'HIM' gas with the possibility of a few embedded lumps of 'CNM', wrapped in 'WIM' and 'WNM'. A number of investigators have reported on the basis of stellar absorption line studies that some dark clouds in the Scorpius-Ophiuchus region of the sky are immersed in 'HIM' gas and could fit the general characteristics of an ISW source. Several such clouds have been spotted, unfortunately at poorly resolved distances, e.g. the Sancisi-Woerden feature in Ophiuchus [8]. This object has been identified as a possible candidate for the ISW role by Crutcher [9]. A much closer cloud has been hypothetically located as near as 0.03 pc (7000 AU) in the ISW upwind direction by Vidal-Madjar [10]. This cloud, our knowledge of whose existence hinges on deuterium/hydrogen imbalance measurements, exhibits densities of 0.1-0.5 atoms/cm^3 and supposedly approaches us at the correct ISW velocity of 20 km/s. The result has been challenged [11], but the debate heatedly continues [12].

Talbot [13] has analysed consequences of the Sun, or any other star, colliding with I/S clouds. These effects would be difficult to predict, but the tendency of the heliopause (astropause) would be to protect the inner solar (stellar) system from the incoming gas and possibly the accompanying dust by pushing a long stellar wind-filled funnel into the cloud's bulk. Simultaneously, the head of this coma – the heliosphere – would be gradually compressed, until at a cloud density of about $n = 330$ atoms/cm^3 (if $V_{ISW} = 20$ km/s) the solar wind would be pushed into the Sun and thus turned off, resulting in a rapid increase in accretion of ISM-material by the Sun. This in turn could be responsible for a strong 'accretion luminosity,' equal to or larger than the present UV and X-ray solar output. Effects of increased insolation upon the Earth climate, as well as the direct impact of a harder Earth's surface cosmic ray and UV (L_α) environment could be drastic.

Even clouds that have densities smaller than those needed to push the heliopause past Earth's orbital (1 AU) distance could have profound effects on mankind. It is conceivable that stellar evolution rates in themselves might be dependent on forces exerted from the outside upon the star's magnetic field. The cause of the 'Small Ice Age' of the 1600's, for instance, which was associated with a general absence of sunspots, may find its resolution in this connection. Lack of tangible data hinders even a prediction on whether such events would cause over-heating, or an equally traumatic deep freezing of our environment.

It is interesting, however, to note that, again according to Talbot, the Sun, in its lifetime thus far, must have traversed about 135 clouds of $n(H) \geqslant 100$ atoms/cm^3 and 16 clouds with $n(H) \geqslant 1000$ atoms/cm^3. It was estimated that at least 50 encounters between clouds and the Sun have resulted in temporary solar wind extinctions, i.e. one such event in every 100 million years! The relevance of all these studies to life on Earth and the history of its biological evolutionary cycles of similar length is obvious.

The Voyager/Pioneer spacecraft represent the first probes mankind has available to sense the fringes of the ISM, and to determine if any gradients in the measurements can be detected – thus giving us the first grip on future climate prediction efforts, planning for such cloud collision events and, perhaps, even their control.

As presently envisioned, four fields and particle instruments are to be utilised during the Voyager post-Neptune Interstellar Cruise. These include:

(1) *The Cosmic Ray Instrument System* (CRS) which consists of a cluster of telescopes to measure the energy spectrum (distribution) of particles between 1 and 500 MeV;

(2) *The Low Energy Charged Particle System* (LECP) investigates the very low energy end of the spectrum by differentiating charged particles by source, composition, energy, flux intensity and favoured direction;

(3) *The Plasma Particles System* (PLS) is concerned with the collective properties of very hot ionised plasma, such as the solar wind, determining its velocity, density, pressure and flow direction and;

(4) *Magnetic Field Experiment* (MAG) – It consists of a high-field and a low-field magnetometer system, HFM and LFM, respectively, the latter of which should be able to detect the heliopause directly by a sudden drop in field intensity.

As stated before, the two Voyagers, along with the two Pioneers, are in an excellent position to provide some early answers to the Heliopause/Interstellar Medium investigation – all four are heading out of the solar 'bubble,' but in four different directions. All of these are shown in Fig. 6, which represents an outsider's view of the heliosphere, as seen looking along the relative velocity vector of the ISW, shown in galactic coordinates. Voyager 1 and Pioneer 11 are heading out into the general direction towards the ISW: Voyager 1 about 29° east (to the left) of it, which takes it right into the plane of the expanding Gould Belt (already shown in Fig. 5), while Pioneer 11 escapes the system some 38° south-east of the ISW. Voyager 2 still has a number of Neptune flyby choices of which the current nominal trajectory escapes solar space some 75° south of the ISW. All three spacecraft cluster just outside the gigantic Radio Loop I, the "North Polar Spur," the nearest supernova remnant, which is in collision with the Gould Belt; this collision may be the progenitor of our ISW. Pioneer 10, on the other hand, presently the most distant man-made object, is leaving the system in the opposite direction – through the heliospheric tail, downwind with respect to the ISW. Destined to investigate the turbulent and probably very long tail, this spacecraft