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CRAF Mission: An Opportunity for Exobiology

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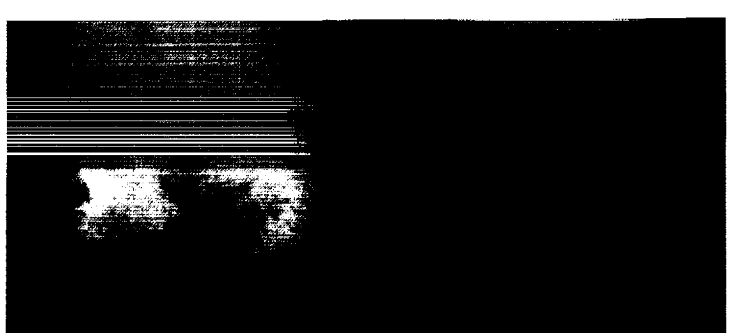
The Halley missions of 1986 gave us a first, quick glimpse of a comet nucleus and the first *in situ* measurements of cometary gas and dust. Many of our basic ideas about cometary nuclei were confirmed while a number of startling new discoveries were also made. However, in many respects the very fast Halley flybys raised more questions than they answered. We learned, for example, that comets contain a large amount of organic material, but we were unable to determine precisely which organic molecules were present. We learned, too, that the nucleus of a comet is a dark, irregularly shaped body, but we could determine very little about the physical state and structure of the ices and grains within the comet nucleus.

On NASA's drawing boards are detailed plans for a space mission to a comet that will answer many of these questions. The Mission is called the Comet Rendezvous Asteroid Flyby, or CRAF. The term rendezvous indicates that the spacecraft will be maneuvered so that it will follow an orbit around the Sun that precisely matches the



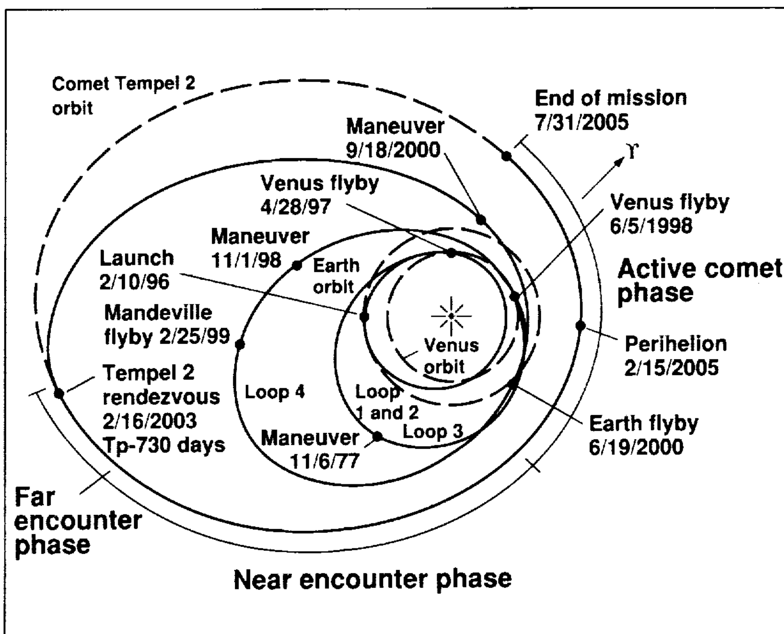
comet's orbit; the spacecraft and the comet will then travel together through one or more complete orbits. En route to the comet, CRAF will also fly by a main belt asteroid and make remote sensing measurements of its properties.

CRAF represents a substantial advance beyond the fast (70 kilometers/second) Halley flybys because a rendezvous mission has the ability to observe the comet on a very fine scale and over a very long period of time, thus allowing studies of the effects of the changing levels of the comet's activity. With a rendezvous mission it is also possible to collect and study cometary material without damaging it and to carry out a program of adaptive exploration so that early results can be used to plan later measurements.

The planned target for CRAF's rendezvous is either comet Kopff or comet Tempel 2, depending on launch date. These are two of the more active of those short-period comets which can be reached for a rendezvous mission. An active comet is preferred over one that has spent so much time in the inner solar system that it has largely exhausted its supply of volatiles. Furthermore, a high level of activity will assure that a substantial supply of gas and dust will reach the orbiting spacecraft for highly accurate *in situ* studies.

A representative CRAF trajectory is shown in figure 12-1. For a launch in February 1996, the spacecraft would initially travel on a complex trajectory that takes it twice past Venus and once past the Earth; the gravity of Venus and Earth will be used to modify the orbit and give the spacecraft sufficient energy to meet up with the target comet. The trajectory to comet Tempel 2 shown in figure 12-1 takes the spacecraft through the asteroid belt, where it will make a close flyby of the asteroid 739 Mandeville. This asteroid, whose diameter is about 110 kilometers, is a member of the primitive type CP spectral class with a surface composition believed to be similar to that of carbonaceous chondrite meteorites. All of the remote sensing instruments (described below) will operate during the asteroid flyby. CRAF will be able to determine the size, shape, mass, and density of the asteroid and obtain data concerning its surface morphology, temperature, and composition. Later launch opportunities to comet Kopff have trajectories similar to the trajectory to Tempel 2 shown in figure 12-1, but the opportunities differ in the asteroids that can be encountered.

Figure 12-1. The orbit of comet Tempel 2 and a representative trajectory of the Comet Rendezvous Asteroid Flyby (CRAF) spacecraft.



For the example mission described above, the CRAF spacecraft would finally reach its destination and be inserted into the same orbit about the Sun as comet Tempel 2 in January 2003. If CRAF is launched in May 1997, it would arrive at comet Kopff in December 2005. In either case, at the time of rendezvous, the comet will be near its aphelion and in a state of minimum activity. From a close orbit around the comet, CRAF will map the entire surface with a battery of imaging and spectroscopic instruments. Multicolor images with a resolution of better than 1 meter will provide details about the size, shape, and surface morphology of the comet nucleus. By analyzing the spectrum of reflected sunlight at visible and near-infrared wavelengths, we will be able to identify different ices and minerals on the comet's surface. The surface temperature distribution will be mapped to determine thermal properties and energy balance as well as to aid in the identification of surface materials. Accurate radio tracking data will be used to determine the mass and higher order gravity harmonics of the comet nucleus. Combined with the imaging data, knowledge of the mass will enable calculation of the comet's bulk density to tell us whether the interior of the nucleus more closely resembles a hard-packed snowball or a newly fallen bank of fluffy snow. This will then tell us how the comet nucleus probably accreted and what processing it might have undergone since its formation.

As it approaches the Sun, the comet will become more active and the spacecraft will move in and out through the comet's atmosphere, collecting dust for on-board analysis of its elemental and chemical properties. Emitted gases will be analyzed for their composition and temperature, and the velocity at which they flow away from the nucleus. The cometary atmosphere and nucleus will be studied as the comet moves along its eccentric orbit, reaching maximum activity near perihelion. During this period of high cometary activity a complete suite of plasma instruments will study the interactions of cometary gas and dust with sunlight and with the solar wind in an effort to achieve better understanding of the processes that control the ever-changing cometary tails, the acceleration of energetic particles, and other important astrophysical phenomena.

A computer drawing of the CRAF spacecraft design is shown in figure 12-2. The spacecraft consists of a central structure, or "bus," containing the electronics, radio transmitters and receivers, computers, and solid state recorders. Above the bus is a 4-meter high-gain antenna supplied by the Italian Space Agency; the antenna is kept pointed at the Earth during most of the Mission. Below is the propulsion system consisting of fuel tanks, main engines, and attitude control thrusters; the propulsion module will be supplied by the Federal Republic of Germany which will also supply one of the scientific instruments. Table 12-1 lists the scientific experiments to be carried on CRAF. Most of the instruments are located on platforms at the ends of booms extending to the right and left of the bus. On the right is the high-precision scan platform, capable of an inertial pointing accuracy of 2 milliradians (0.1 degrees),

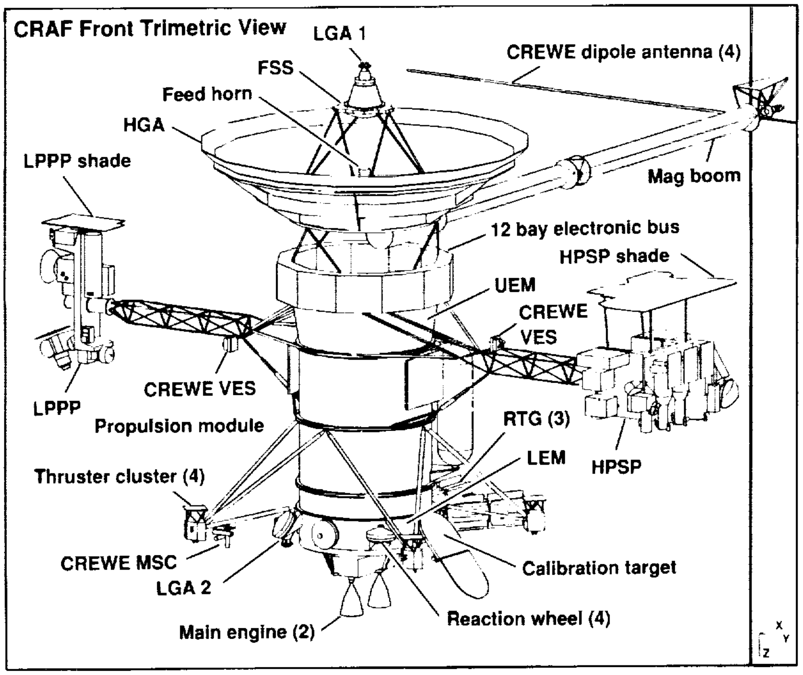


Figure 12-2. The CRAF spacecraft.

and carrying narrow- and wide-angle CCD cameras, a visual and near-infrared imaging spectrometer, and a thermal infrared radiometer. The low precision scan platform on the left has a pointing accuracy of 1.0 degree and carries the gas and dust sampling and analysis instruments. Magnetometers and plasma wave antennas are mounted on an extendable mast behind the bus. Three radioisotope thermoelectric generators are mounted on a short boom behind the bus and provide nearly 700 watts of power.

In addition to the science teams that provide instruments, the CRAF science team includes the five Interdisciplinary Scientists (IDS) identified in table 12-2. The role of the IDS for exobiology is to educate the instrument teams concerning the exobiological importance of their experiments, to help optimize the instrument designs and the exploration strategy for the study of exobiology, and to aid in the synthesis and interpretation of results in an exobiological context.

The foregoing discussion has highlighted the principal features of the CRAF Mission in a very general way. In the rest of this paper, we focus on and describe in greater detail those CRAF measurements which are expected to be of the greatest relevance to exobiology.

The CRAF measurements aimed at deeper understanding of chemical evolution in comets are symbolically summarized in figure 12-3. The outer arcs of the figure summarize the three principal questions to be addressed: (1) What biogenic materials are present in comets? (2) To what extent, and how, have these materials been synthesized into complex, biochemically interesting molecules? (3) Is there any evidence that substantial amounts of cometary material have been delivered to the planets in general and to the Earth in particular?

Table 12-1: CRAF Science Investigations

Acronym	Investigation	Principal Investigator/ Team Leader	Institution
ISS	Imaging (Facility)	Joseph Veverka	Cornell University
VIMS	Visual/infrared mapping spectrometer (Facility)	Thomas B. McCord	University of Hawaii
TIREX	Thermal infrared radiometer experiment	Francisco P. J. Valero	NASA Ames Research Center
CoMA	Cometary matter analyzer	Jochen Kissel	Max-Planck-Institut für Kernphysik
CIDEX	Comet ice/dust experiment	Glenn C. Carle	NASA Ames Research Center
CODEM	Comet dust environment monitor	W. Merle Alexander	Baylor University
NGIMS	Neutral gas and ion mass spectrometer	Hasso B. Niemann	NASA Goddard Space Flight Center
CRIMS	Comet retarding ion mass spectrometer	Thomas E. Moore	NASA Marshall Space Flight Center
SPICE	Suprathermal plasma investigation of cometary environments	James L. Burch	Southwest Research Institute
MAG	Magnetometer	Bruce Tsurutani	Jet Propulsion Laboratory
CREWE	Coordinated ratio, electrons, and waves experiment	Jack D. Scudder	NASA Goddard Space Flight Center
RSS	Radio science (Facility)	Donald K. Yeomans	Jet Propulsion Laboratory

To answer the first question, we need to inventory the elemental composition of the icy, organic, and nonvolatile components of cometary material. We wish to know not only the abundances of the principal biogenic elements H, C, N, O, P, and S, but also the other elements considered important to life, including Mg, Ca, Fe, Si, Na, Cl, K, Cr, Mn, and Ni, and the biochemically active trace elements such as Co, Cu, Zn, As, Se, Mo, Cd, Sn, and I.

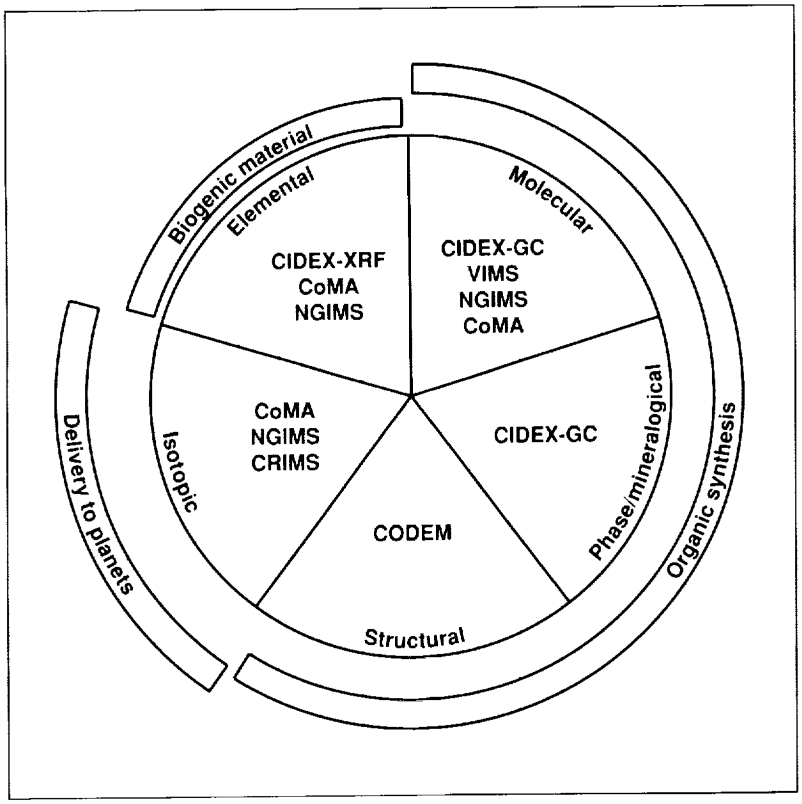
Table 12-2: Interdisciplinary Scientists for CRAF

Topic	Name, Institution
Asteroid and inactive nucleus	David Morrison, NASA Ames
Active nucleus and dust	Armand Delsemme, University of Toledo
Exobiology	Christopher P. McKay, NASA Ames
Coma	Walter F. Huebner, Southwest Research Institute
Solar wind interaction	D. Asoka Mendis, University of California, San Diego

For the second question, we want to know not only which molecules exist in comets, but what the circumstances of their formation and preservation were. The different minerals and the different phases of ice found in cometary nuclei carry information about the pressure and temperature at the time and location of condensation. A very porous grain structure might be indicative of surface catalysis of the synthesis of complex molecules in comets. We also wish to know whether high-activity, nonequilibrium, or chemically incompatible compounds or radicals are frozen into cometary ices, and if so, at what temperatures they are released and become active. Complete answers to the second question therefore require an inventory of the molecular composition together with knowledge of the mineralogy or crystal structure of both the volatile and nonvolatile material and the fine-scale physical structure.

With respect to the third question, the best indicator of the contribution of cometary material to the planets probably lies in the comparison of specific isotopic ratios in comets and in the receiving medium, such as the Earth's atmosphere and oceans. The deuterium to hydrogen ratio is one of the more useful isotopic ratios for this purpose.

Figure 12-3. The relation between the exobiological objectives of CRAF, the parameters that need to be measured, and the CRAF instruments that make each type of measurement.



The pie sectors in figure 12-3 represent the five properties—elemental, molecular, and isotopic compositions together with mineralogical and physical structures—that must be measured to address the three basic questions. The acronyms and abbreviations in each of the sectors in the figure indicate which CRAF instruments contribute to measurements of each of the five properties. In the following paragraphs, we describe each of these instruments and how they will obtain the information we want.

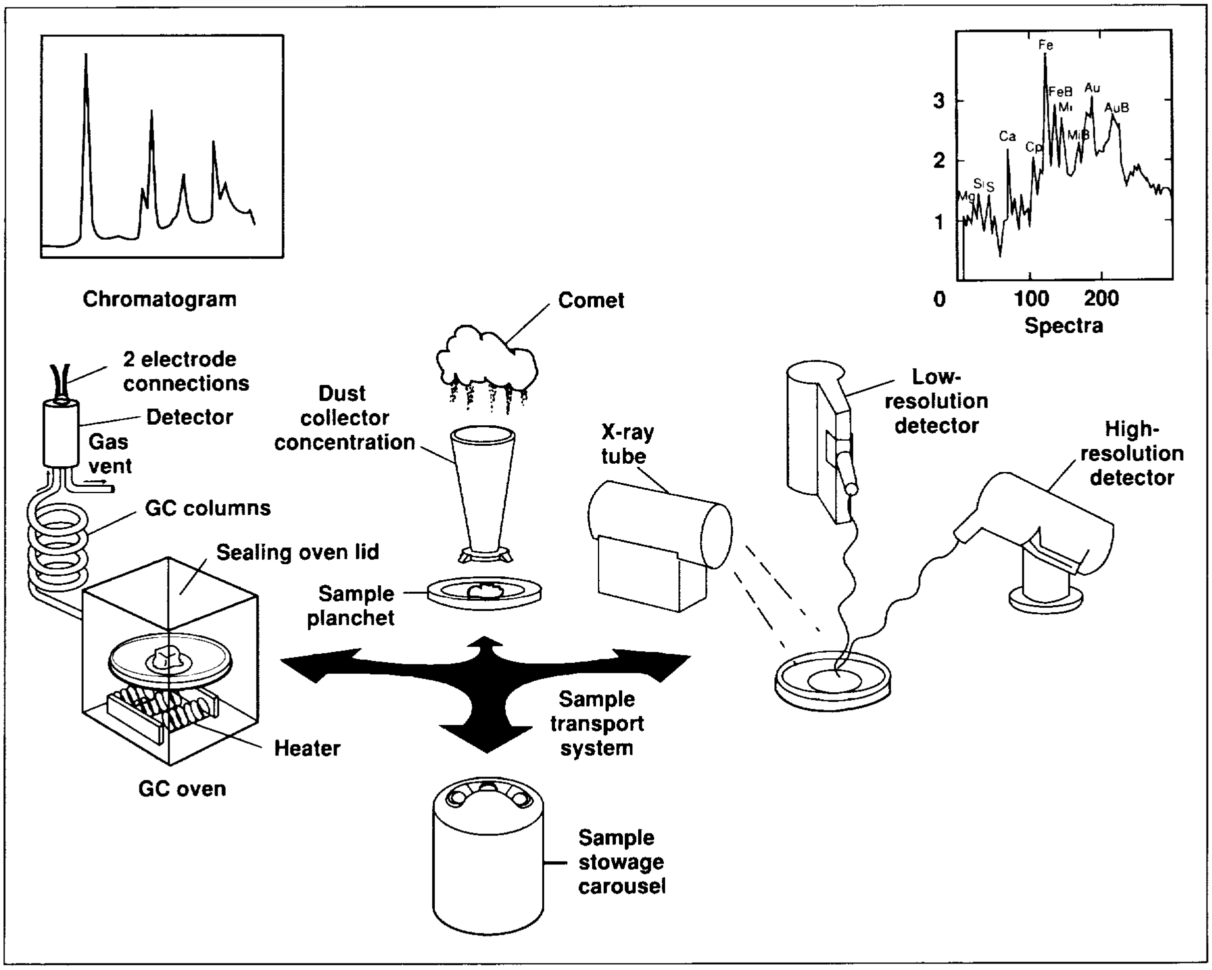


Figure 12-4. Diagram of the basic functions of the Cometary Ice and Dust Experiment (CIDEX).

Cometary Ice and Dust Experiment (CIDEX): The functions of CIDEX are illustrated in figure 12-4. This instrument will passively collect samples of ice and dust as the spacecraft moves in and out through the comet's coma and will then pass each sample back and forth between an x-ray fluorescence spectrometer (XRF) and a pyrolysis oven linked to a set of gas chromatograph columns (GC). In the XRF analyzer, the bulk sample will be irradiated by x-rays or alpha particles which excite secondary or fluorescent x-rays whose characteristic energies can be used to identify the abundances of 15 to 25 elements with nuclear mass of 6 or greater. After XRF analysis, a sample will be moved to a pyrolysis oven where it will be heated to a preselected temperature and the gases released during heating will be analyzed with three, possibly four, gas-chromatograph columns. There will be one column for light gases (Na, H_2, N_2, Ar, and CO), one for polar molecules (H_2O, CO_2, SO_2, H_2S, COS, HCN, CH_3CN, NH_3, CH_2O, and CH_3OH), and one

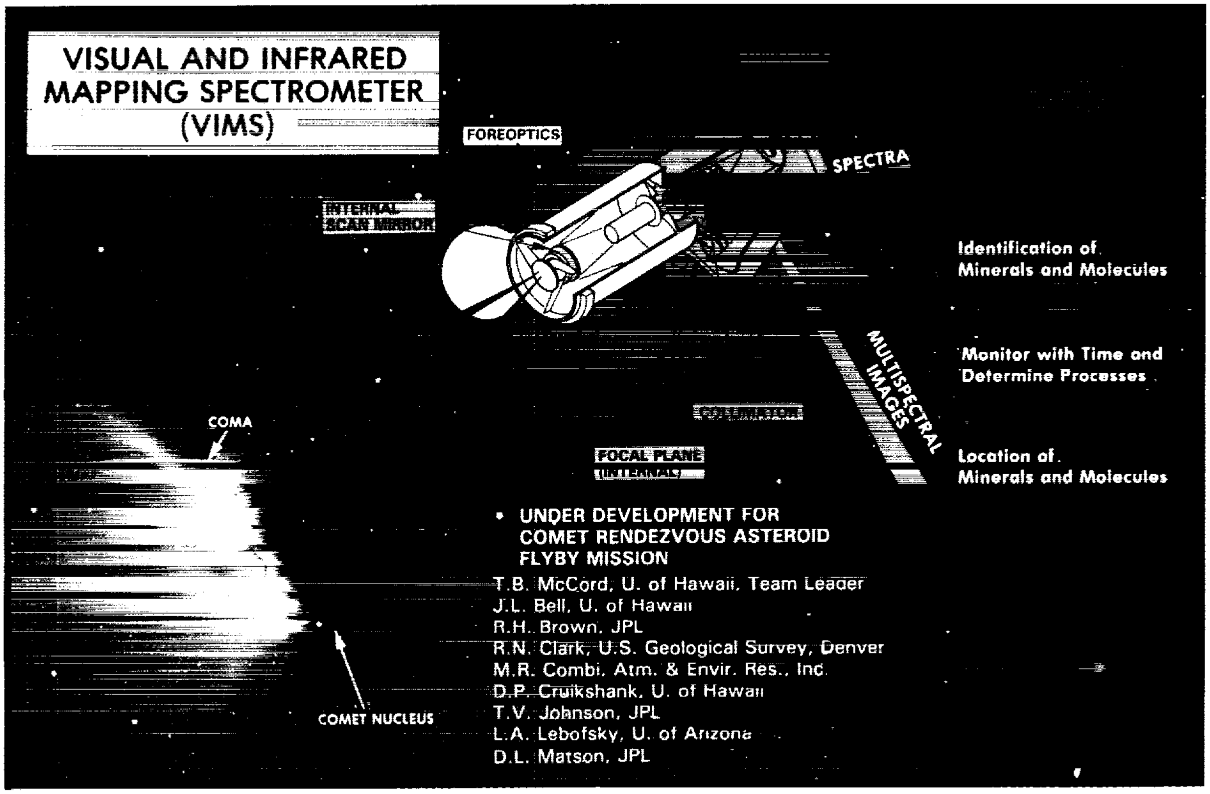


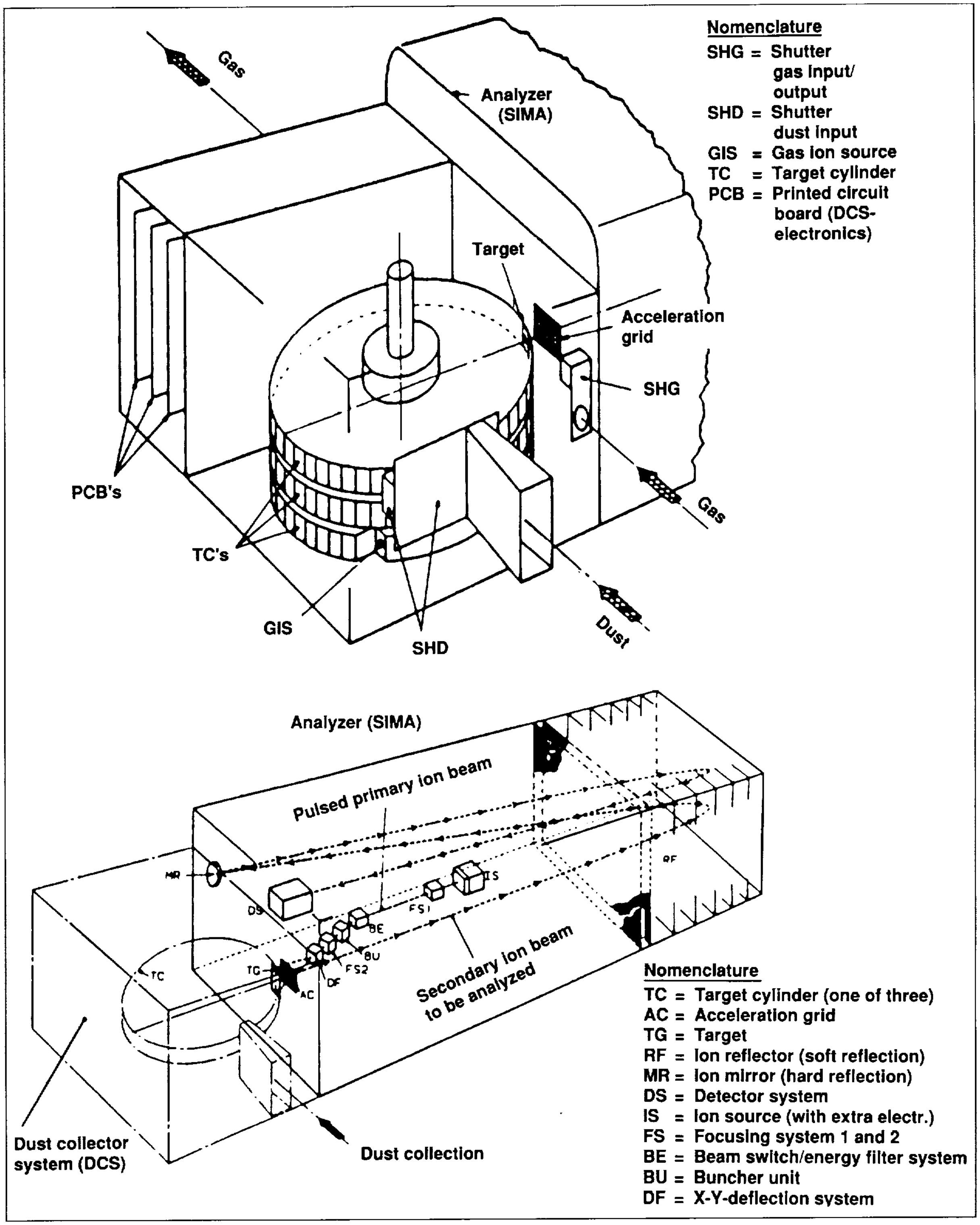
Figure 12-5. Diagram of the Visual and Infrared Mapping Spectrometer (VIMS).

for organics (all molecules with 1 to 4 carbon atoms, and some with as many as 8 carbon atoms in a molecule). The measurement cycle will consist of an XRF analysis, pyrolysis, analysis of the evolved gases with the GC, another XRF analysis to measure changes in composition, pyrolysis to a higher temperature, etc. The final step will consist of oxidizing the sample at about 800°C and then analyzing the combustion products with the GC.

Visual and Infrared Mapping Spectrometer (VIMS): VIMS will map the asteroid and the nucleus and coma of the comet in each or any of 320 spectral bands between 0.35 and 5.1 micrometers. The main elements of the VIMS instrument are shown in figure 12-5. When the comet is inactive, VIMS is expected to identify minerals and ices on the nucleus surface and to measure their abundances, distributions, and changes in time. Surface materials that can be identified by VIMS include silicates, ices, organics, oxides, salts, metals, and emitting ions. When the comet is active, VIMS will obtain maps of many of the more abundant molecules and radicals in the coma, such as CN, HCN, H_2O, H_2CO, OH, CH_4, C_2, C_3, and CO_2.

Cometary Matter Analyzer (CoMA): This instrument is based on the Secondary Ion Mass Spectrometry (SIMS) technique. A diagram is shown in figure 12-6. Samples

Figure 12-6. Diagram of the Cometary Matter Analyzer (CoMA).



of dust will be collected and then bombarded by a pulsed ion beam. The secondary ions released as a result of this bombardment will be analyzed in a time-of-flight mass spectrometer. Because of the very long path length of the mass spectrometer, very high mass resolution ($m/\Delta m \geq 3000$) can be achieved, which will allow separation of different species with the same atomic weight—such as ^{12}CH versus ^{13}C, or CO versus N_2. Thus the CoMA instrument will be very important for the measurement of isotopic ratios of cometary material. CoMA will be able to measure very heavy molecules—with molecular weights up to 3000 atomic mass units. The instrument will also be operated in different modes that enable it to measure compositional depth profiles of individual grains or to obtain mass spectra of the gas or thermal ions in the comet's coma.

Neutral Gas and Ion Mass Spectrometer (NGIMS): A diagram of NGIMS is given in figure 12-7. This instrument can analyze the gas which enters through any of four apertures:

1. An open or fly-through aperture which will use a molecular beam technique to analyze reactive species without letting them hit any walls where they might recombine;

2. A closed source, which will allow concentration of nonreactive species;

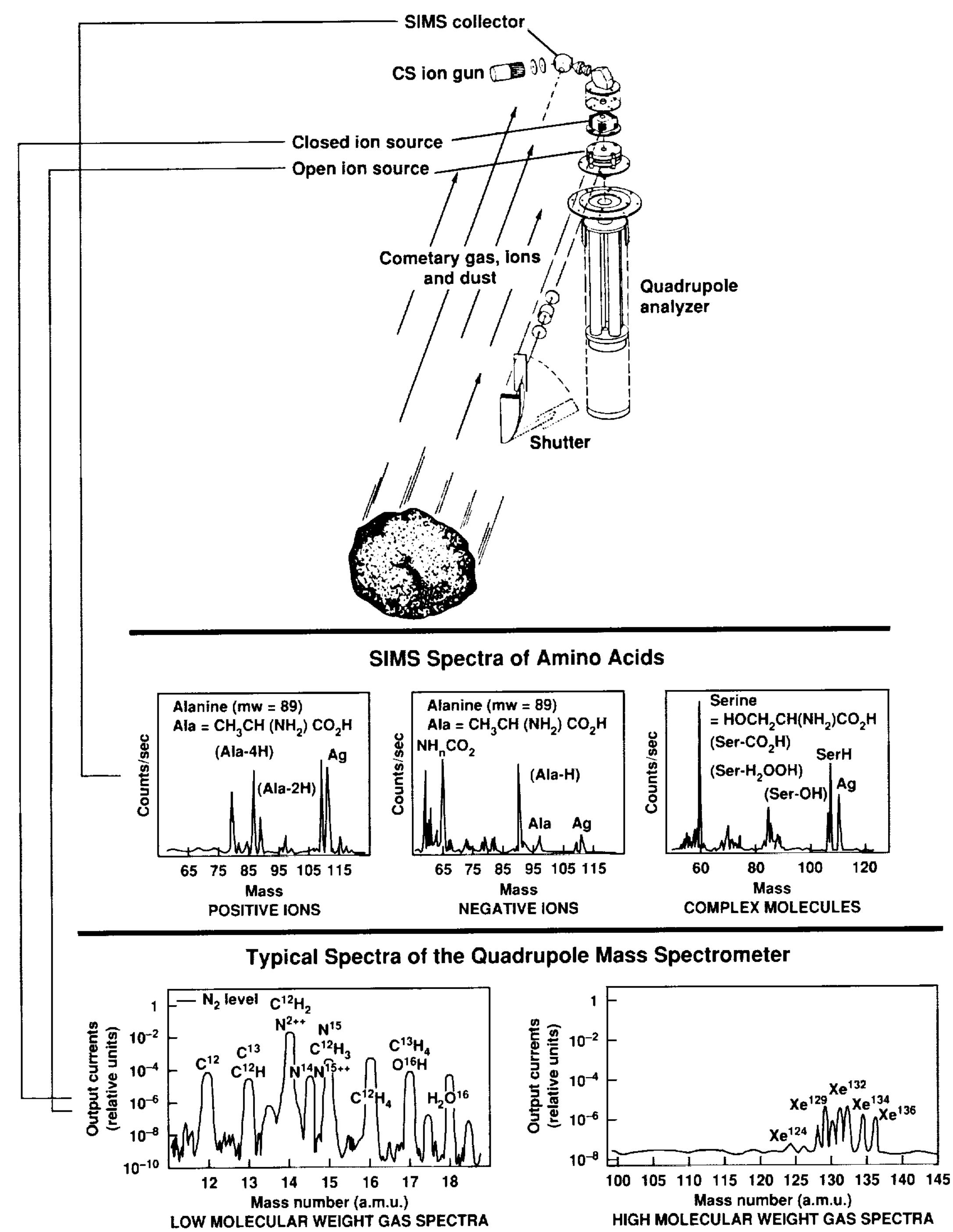
3. A thermal ion source; and

4. A SIMS source which consists of a cold metal surface that will efficiently trap heavy organic species and then occasionally gently sputter them from the surface by ion bombardment.

The mass range of this instrument is 1-300 atomic mass units. This mass spectrometer and the gas analysis mode of CoMA will obtain complementary data; the NGIMS has high sensitivity (2×10^{-3} counts/molecule/cubic centimeter) but relatively low mass resolution ($\Delta m = 0.5$ atomic mass units), while CoMA has very high mass resolution, but two orders of magnitude less sensitivity.

Cometary Retarding Ion Mass Spectrometer (CRIMS): Because most of the chemistry occurring in the comet's coma involves ion-molecule reactions, measurement of the abundance of different ion species will be of great aid in interpreting the mass spectrum obtained by NGIMS. Complete physical/chemical models of the coma will be required to interpret the observed mass spectrum in terms of chemical species. Quite sophisticated modeling will be required, for example, to sort out how much of the mass is equal to a 17 atomic mass units peak observed by NGIMS may be due to the OH radical and how much due to NH_3, or how much of the mass/charge is equal to an 18 atomic mass units/charge peak observed by CRIMS may be due to H_2O^+ and how much due to NH_4^+. Data from both NGIMS and CRIMS, as well as electron temperature data from other instruments on CRAF, are required for the unambiguous interpretation of either set of data.

Figure 12-7. Basic concept of the Neutral Gas and Ion Mass Spectrometer for the CRAF Mission.



- To measure the chemical composition of the neutral gas in the coma of the comet.
- To measure the composition of the low-energy ions in the coma of the comet.

Cometary Dust Environment Monitor (CODEM): To determine the dust particle size distribution, CRAF will also carry an instrument to record the flux of very small solid particles. The principal detector of this instrument is a very sensitive microphone that listens for and records the magnitude and frequency of particle impacts.

Conclusion

Returning to figure 12-3, we can now comment on the apparent overlap of measurements in each of the five pie sectors. The various measurements will, in fact, be complementary, rather than redundant. For example, the several measurements of elemental composition will be complementary because the CIDEX-XRF will determine the elemental abundance of bulk samples of dust, CoMA will obtain high-resolution mass spectra of both grains and gas, while NGIMS will measure the composition of gas and thermal ions at high sensitivity, but lower resolution. Similar complementarity is found in each of the five pie sectors. Some instruments will measure the nucleus or its surface, some the gas, and some the dust. Furthermore, some types of measurements will help resolve ambiguities in other types of measurements. For example, comparison of gas chromatograph results with molecular weight spectra obtained by NGIMS and CRIMS and with observations of spectral lines of coma gases by VIMS will give us three independent types of measurements, with a much reduced chance of confusion and ambiguity.

In summary, the Comet Rendezvous Asteroid Flyby Mission provides an opportunity for significant advances in our knowledge of the primitive, yet complex material in a short-period comet and on the surface of an asteroid. CRAF will obtain new information concerning the early environments of the outer solar system and the asteroid belt and of the extent of chemical evolution in such environments. Comparison of data from the asteroid flyby and the comet rendezvous with results of studies of interplanetary dust and meteorites will elucidate the relations between these different solar system objects. The results of the CRAF experiments should also give us a clearer picture of how the primitive bodies, the comets and asteroids, and their interplanetary debris may have contributed to the origin of life on Earth.

Additional Reading

Astronomy and Astrophysics, vol. 187, 1987.

Draper, R. F.: The Mariner Mark II Program. AIAA Paper 88-0067, 1988.

Neugebauer, M.: Comet Rendezvous—The Next Step. Sky and Telescope, vol. 73, 1987, p. 266.