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ORIGINAL ARTICLE

Kronos: exploring the depths of Saturn with probes and remote sensing through an international mission

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Abstract *Kronos* is a mission aimed to measure in situ the chemical and isotopic compositions of the Saturnian atmosphere with two probes and also by remote sensing, in order to understand the origin, formation, and evolution of giant planets in general, including extrasolar planets. The abundances of noble gases, hydrogen,

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carbon, nitrogen, oxygen, sulfur and their compounds, as well as of the D/H, $^{4}He/^{3}He$, $^{22}Ne/^{21}Ne/^{20}Ne$, $^{36}Ar/^{38}Ar$, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/(^{17}O)/^{16}O$, $^{136}Xe/^{134}Xe/^{132}Xe/^{130}Xe/^{129}Xe$ isotopic ratios will be measured by mass spectrometry on two probes entering the atmosphere of Saturn at two different locations near mid-latitudes, down to a pressure of 10 Bar. The global composition of Saturn will be investigated through these measurements, together with microwave radiometry determination of H_2O and NH_3 and their 3D variations. The dynamics of Saturn's atmosphere will be investigated from: (1) measurements of pressure, temperature, vertical distribution of clouds and wind speed along the probes' descent trajectories, and (2) determination of deep winds, differential rotation and convection with combined probe, gravity and radiometric measurements. Besides these primary goals, Kronos will also measure the intensities and characteristics of Saturn's

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magnetic field inside the D ring as well as Saturn's gravitational field, in order to constrain the abundance of heavy elements in Saturn's interior and in its central core. Depending on the preferred architecture (flyby versus orbiter), Kronos will be in a position to measure the properties of Saturn's innermost magnetosphere and to investigate the ring structure in order to understand how these tiny structures could have formed and survived up to the present times.

Keywords Saturn · Atmosphere · Probes · Cosmic vision

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1 Introduction

Giant planets are mostly made of the gas that was present in the protosolar disk before the terrestrial planets accreted (Fig. 1). Their comparative study is thus essential to understand planet formation in general and the origin of the Solar System. Saturn in particular appears to be a natural target for near-future exploration, after the fine characterization of Jupiter by Galileo and Juno and before future ambitious missions to Uranus and Neptune. Saturn, the ring planet, is mysterious in many aspects, and plays a key role to understanding planet formation, the evolution of solar and extrasolar giant planets, planetary meteorology, magnetospheric interactions, dynamo generation and the physics of planetary rings.

Saturn, like Jupiter, has an atmosphere that appears to be enriched in elements other than hydrogen and helium with respect to the solar composition. This enrichment may be the result of planetary precursors formed at low temperatures, or of a progressive enrichment of the protosolar disk, with profound consequences for understanding the formation of the Solar System. The different formation scenarios that result can be disentangled by a study of the atmospheric composition of Saturn in noble gases and major volatile (H, C, N, S, O) elemental and isotopic compositions, which requires in situ measurements Table 1.

Noble gases are particularly relevant in this study, because: (1) they are chemically inert and their abundances are determined by physical processes such as phase partitioning, and (2) their isotopic compositions present large-scale inhomogeneities between the original protosolar nebula composition and sub-reservoirs of the solar system that make them isotopic tracers as well. Indeed, analyses of meteorites point to the existence of a primordial reservoir of volatiles

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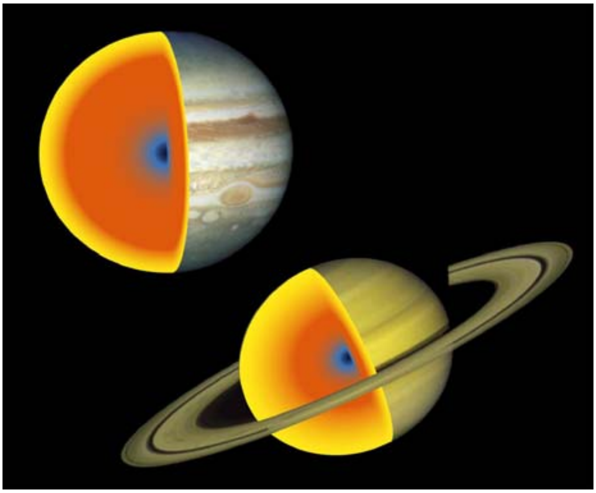

Fig. 1 Interiors of Jupiter and Saturn highlighting the importance of hydrogen and helium for the structure of these two planets (*yellow* indicates that hydrogen is in molecular form, *red* that it is metallic, and the central dense core is shown in *blue*)

with an isotopic composition different from that of the Sun. The discovery of this reservoir through its isotopic signature in Saturn's atmosphere would have a direct impact on the primordial history of the Solar System and on the study of meteorites and comets. Generally, the elemental and isotopic determinations of Saturn's atmospheric composition would permit to explore sources of matter and processes of formation for the giant planets.

Table 1 Composition measurements in Saturn's deep atmosphere and their consequences

Species	Consequence
He	Determine extent of helium sedimentation in Saturn's interior. Crucial for accurate understanding of the thermal evolutions of Saturn and Jupiter
Ne	Test prediction of Ne capture in He droplets. Refine H–He phase separation diagram
CH_4	Fine determination crucial to understand the formation of the planet
NH_3 NH_4SH	Key to decide between models of planetesimal delivery and planet formation. Important for Saturn's meteorology
H_2S NH_4SH	Key for planetesimal delivery, with possibility that the abundance is linked to that of rocks deep inside. Important for Saturn's meteorology
H_2O	(by radiometry); Key to understand the planet's structure, formation, and meteorology
Ar, Kr, Xe	Key to decide between models of planetesimal delivery and planet formation. Link with the compositions of the Sun and protosolar disk
CO, PH_3, AsH_3, GeH_4	Disequilibrium species are important to understand convection in Saturn's deep atmosphere. Help to further test planetesimal delivery models
D/H	Test models that predict it should be similar to Jupiter and to the protosolar value
$^{12}C/^{13}C$	Test models that predict value similar to Earth
$^{14}N/^{15}N$	Important to understand whether N was delivered as N_2 or as NH_3. Test models of planetesimals delivery
$^{20}Ne/^{22}Ne$	Origin of gas, Test evaporation processes in the early solar system
$^{36}Ar/^{38}Ar$ Kr, Xe isotopes	Origin of gas, Test evaporation processes of these gases in planetesimals

Another means to better understand the formation of the Solar System is through a determination of the planet's core mass and global composition: we do not yet know whether Saturn possesses more or less heavy elements than Jupiter, and we do not know which planet has the largest core. This impacts directly on the formation models of these planets and of the Solar System as a whole.

Saturn is also fascinating for its intriguing meteorology. Contrary to Jupiter, whose rotation axis is almost perpendicular to its orbit, Saturn has an inclination of 20° (similar to that of the Earth), plus rings which lead to marked seasonal variations. Perhaps as a result of this, Saturn undergoes the most intense storms of the Solar System, with planet-wide events that can last for months. Its zonal wind pattern is similar to Jupiter, but appears to vary significantly, as shown by the mysterious slowing of Saturn's equatorial jet from 450 m/s in the Voyager era, down to 250 m/s at the arrival of the Cassini spacecraft. Two key elements are missing to model the causes of these variations: Saturn's deep water abundance as a powerful source of convective potential energy, and Saturn's deep rotation field.

Another surprising finding of the Cassini–Huygens mission has been the fact that Saturn's magnetic field is considerably modified by the rings, with two consequences: (1) our inability to measure the deep rotation rate in the magnetic dynamo region; (2) the impossibility to measure the planet's true magnetic field, but instead, a filtered, perfectly asymmetric field. A measurement of the planetary magnetic field inside the D ring would provide the data necessary to understand the planet's magnetic field generation and to analyze gravity data using proper constraints on the rotation rate.

The next section discusses the primary scientific goals that are driving the mission, namely the study of the origin of the Solar System and the study of planetary atmospheres, as well as the secondary goals which require a feasibility assessment, and finally the physics of magnetic fields and of planetary rings.

2 Science objectives

2.1 Planet formation and the origin of the solar system

Saturn and Jupiter formed 4.55 Ga ago, from the same disk of gas and solids that formed the Sun and eventually the entire Solar System (e.g., [1]). A significant fraction of their mass is composed of hydrogen and helium, the two lightest and most abundant elements in the Universe. Disks with hydrogen and helium are almost ubiquitous when stars appear, but these disks fade away rapidly, on timescales of only a few million years (e.g., [2]). This implies that Jupiter and Saturn had to form rapidly in order to capture their hydrogen and helium envelopes, more rapidly than e.g. terrestrial planets which took tens of millions of years to attain their present masses, and retained only negligible amounts of the primordial gases as part of their final composition. Thus by studying these giant planets, we have access to information on the composition and early evolution of the protosolar disk that led to the birth of the *entire* Solar System.

In spite of the recognition of the importance of such knowledge, data on the composition and structure of the giant planets, which hold more than 95% of the mass of the Solar System, excluding the Sun, remains scarce. The masses of the central cores of Jupiter (0 to 15 $M_\oplus$ where $M_\oplus$ is the mass of the Earth) and of Saturn (8 to 26 $M_\oplus$), as well as the total masses of heavy elements (10 to 40 $M_\oplus$, and 20 to 30 $M_\oplus$, respectively) are poorly constrained [3]. Along the same lines, the abundance of oxygen, the third most abundant element in the Universe after H and He and a key element for planetary formation, is unknown in the well-mixed atmospheres of both Jupiter and Saturn [4]. Jupiter's composition was measured in situ by the Galileo probe in 1995 down to a pressure level of 22 Bar [5]. On Jupiter, the abundances of 8 major elements have been measured, while in contrast, on Saturn we only have reliable data for C, He, and model-dependant results on N and S (Fig. 2). The Galileo measurements at Jupiter include a highly precise determination of the planet's helium abundance, crucial for calculations of the structure and evolution of the planet.

Several key species (carbon, nitrogen, sulfur, argon, krypton and xenon), were found to be enriched in Jupiter's atmosphere compared to the solar composition mixture, which directly impacts theories on the formation of the Solar System. Figure 2 shows that planet formation models that attempt to reproduce the abundances measured in Jupiter yield very different results for Saturn, with key elements being oxygen (in the form of water) and the noble gases. Specifically a model based on direct adsorption on low-temperature planetesimals yields a high, uniform enrichment of all species other than H, He and Ne [5]. A model in which gases are trapped into crystalline ice as clathrates yields a very non-uniform enrichment of these species (e.g. [7, 8]). If the noble gases were not delivered

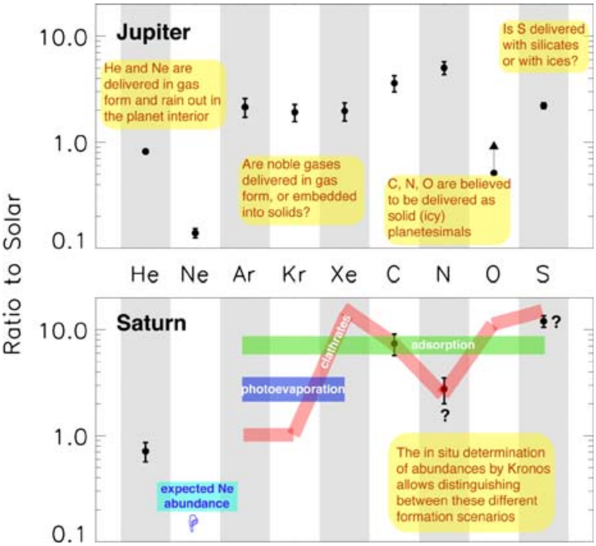

Fig. 2 Elemental abundances measured in the tropospheres of Jupiter (*top*) and Saturn (*bottom*) in units of their abundances in the protosolar nebula (from [6]). The elemental abundances for Jupiter are derived from the in situ measurements of the Galileo probe. The abundances for Saturn are spectroscopic determinations from Cassini for He/H and C/H, and model-dependant ground based measurements for N/H and S/H. Note that the retrieval of the helium abundance is indirect and uncertain, so that very precise He/H measurement is needed. Kronos will allow distinguishing between different formation scenarios whose predictions are shown as *green*, *blue* and *pink curves*, respectively (see text)

directly with the solids but as gas in a protosolar disk enriched in heavy elements by photoevaporation, one then expects enrichments in noble gases that are decoupled from other species and comparable to those found on Jupiter [3, 9]. The processes that formed the giant planets have implications for the other planets as well.

Kronos can therefore directly test scenarios of the formation of the solar system. In particular, Jupiter's nitrogen is highly depleted in ^{15}N by up to 40% compared to "planetary" N found in terrestrial planets and meteorites [10]. Together with measurements of lunar soils irradiated by the solar wind [11], this has led to the concept of an originally ^{15}N-depleted protosolar nebula gas, in which variable extents of ^{15}N-rich solid material were injected so as to yield the large range of N isotopic variations found among the solar system objects. Thus the ^{15}N/^{14}N ratio of the giant planetary atmospheres is expected to vary depending on the mixing ratio of solid and gaseous components that contributed to their formation, and a comparison between Jupiter and Saturn will yield information on the nature and strength of the contributing cosmochemical sources.

Noble gases are also excellent tracers for the origin and the evolution of major solar system reservoirs. Measurements of noble gas (Kr and Xe) isotopic ratios will also be of considerable importance for (1) assessing potential genetic relationship between solar system reservoirs and giant planet atmospheres, and (2) investigating possible atmospheric processes that might have fractionated atmospheric elements. For instance, cometary grains returned by the Stardust mission host a Ne component with an isotopic composition reminiscent of organic matter trapped in primitive meteorites rather than that of the solar nebula [12]. The measurement of the noble gas composition of the Saturn atmosphere is therefore requested to investigate the origin of Saturn atmospheric gases.

Other key measurements include the speciation and stable isotopic compositions of light elements (H, C, N, S) as well as trace gas species abundances (notably AsH_3, PH_3, GeH_4, CO). Last but not least, the very precise measurement of the helium and neon abundances will be the key to an understanding of the formation of helium droplets in the planet's interior and thus the evolution of Saturn and Jupiter (e.g., [13]).

Kronos will also allow us to obtain a measurement of Saturn's gravity field to be performed with unprecedented accuracy. Even from a single flyby of the carrier spacecraft, the close polar orbit and the use of both X and Ka bands guarantees improvements of several orders of magnitude compared to the measurements by Cassini–Huygens (Fig. 3). These accurate measurements will yield stringent constraints on the planetary interior structure. An important source of uncertainty for models is the unknown interior rotation of the planet. The determination of high order harmonics of the gravity field will allow a determination of whether Saturn's interior rotates as a solid body or not [14]. Additional constraints from the magnetic field measurements, radiometric measurements and similar observations at Jupiter with Juno will help precise the state of rotation of Saturn's interior. With further constraints on the helium and oxygen abundance measurements and on the basis of present models of Saturn's internal structure, we expect to determine the mass of the central core to within 10–20% accuracy, and to evaluate whether or not a layer of helium surrounds its core.

A combined analysis of in situ and remote Kronos measurements of Saturn's composition, global water abundance, high accuracy gravity and magnetic fields will

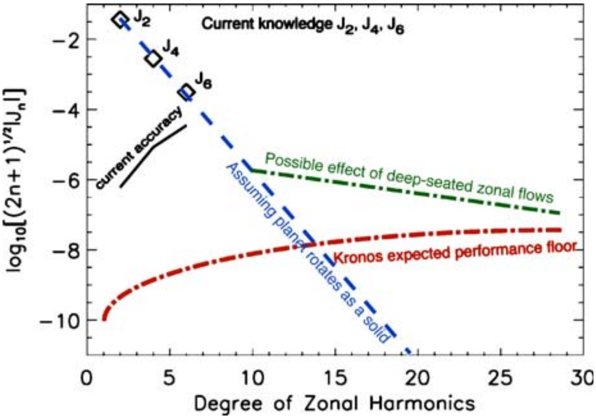

Fig. 3 A comparison of Saturn's currently measured gravitational moments to expected values depending on Saturn's deep rotation state (solid vs. deep-seated zonal flows), and Kronos expected performances based on Ka-band radio measurements during one or several polar fly-bys (based on similar calculations for Jupiter and the Juno spacecraft)

provide us with a detailed view of the planet's structure (Fig. 3). The comparison with similar measurements at Jupiter will yield a unique set of data that will permit us a global understanding of the evolution of the giant planets and their formation within the solar system. Within the next 20 years, we expect thousands of extrasolar planets to be characterized, but with only limited information (e.g. mean density, major atmospheric gases). The parallel study of Saturn and Jupiter enabled by Kronos is fundamental to understand giant planets both from a global statistical perspective, and in fine detail.

2.2 Meteorology and atmospheric dynamics

The dynamics and circulation of gaseous giant planetary atmospheres are important physical attributes for many disciplines, not only for planetary meteorology. Heat transport within the atmosphere and exchanges with the deep interior are crucial factors, affecting the long term evolution of the planet. Chemical transport/mixing within the atmosphere and interior are also of great importance to understand how the composition and structure of a giant planet has evolved since its formation. In addition, an understanding of the circulation, origin and maintenance of the jets, instabilities, waves and vortices in the atmospheres of all of the outer planets is of great interest for comparative planetary meteorology and oceanography. The belt-zone structure of zonal jets in the atmospheres of Jupiter and Saturn is especially relevant at the present time, in the light of the emerging discovery of apparently dynamically similar zonal structures in the Earth's oceans (e.g. [15] and new measurements of eddy momentum transports on Saturn from Cassini [Del Genio, 2007 #1686].

Up to the present time, cloud motion tracking from the Voyager 1 and 2 spacecraft in 1981, ground-based and Hubble Space Telescope since 1991 and the Cassini Orbiter since 2004, has been one of the main methods used to infer aspects of the general circulation of the planet (Fig. 4) [18–22]. A major and persistent problem is that the rotation period taken as a reference frame for the atmospheric motions is not fixed from radio-rotation measurements, and ranges between 10 hr 39 min 24 s and 10 hr 46 min [18, 23–25]. Recent measurements of Saturn's gravity field even

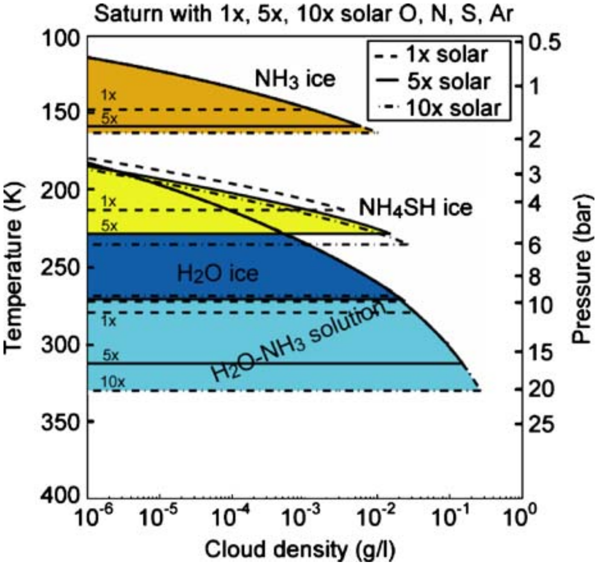

Fig. 4 Mean vertical distribution of cloud layers on Saturn, deduced from a simple thermochemical model [4, 16, 17]

suggest an interior rotation period as short as 10 hours 32 min [26]. As with Jupiter, Saturn's cloud-level meteorology may extend much deeper into its convective interior than the shallow 'weather layer' within which the observed patterns of wind and clouds may be observed from space. Observational constraints on such (deep) atmospheric dynamics are very difficult to obtain, not least because of some fundamental 'degeneracies' in the near-surface signatures of deep and shallow circulations—i.e. very different processes (deep or shallow) may produce surface signatures that are more or less indistinguishable. A major objective of Kronos is therefore to obtain measurements (especially of Saturn's detailed gravity field; see Fig. 3) that can resolve some of these ambiguities and ascertain which aspects of Saturn's meteorology and circulation are deep-seated and which are shallow.

Images in the visual range by spacecraft have captured a plethora of meteorological phenomena immersed within the alternating pattern of zonal jets (Fig. 5), including: (1) cyclonic and anticyclonic eddies with closed circulations and sizes ranging from ~1,000–5,000 km [27, 28]. Particularly interesting is the strong cyclonic vortex found around the Southern Pole [18]. (2) Convective storms are relatively common at mid-latitudes [29, 30] and probably fuelled by "moist" ammonia and water vapour latent heat release [31]. A major event are the "Great White Spots" (GWS) that occur sporadically in Saturn (mainly at equatorial latitudes) attaining a size of 20,000 km before they spread zonally [32]. (3) Waves of different types have been detected at cloud level and in temperature maps. Most significant are those seen at cloud level on Saturn, as for example the mid-latitude northern "ribbon" that moves with a speed of 145 ms^{-1} [33] (Sromovsky et al. 1983), and the "hexagon" that surrounds the northern pole at 78° North [34] that appears to remain roughly stationary with respect to the planet rotation, at least as measured by the Voyager spacecraft.

This variety of meteorological phenomena are observed at clouds and hazes vertically distributed above the ammonia condensation level. The properties of the

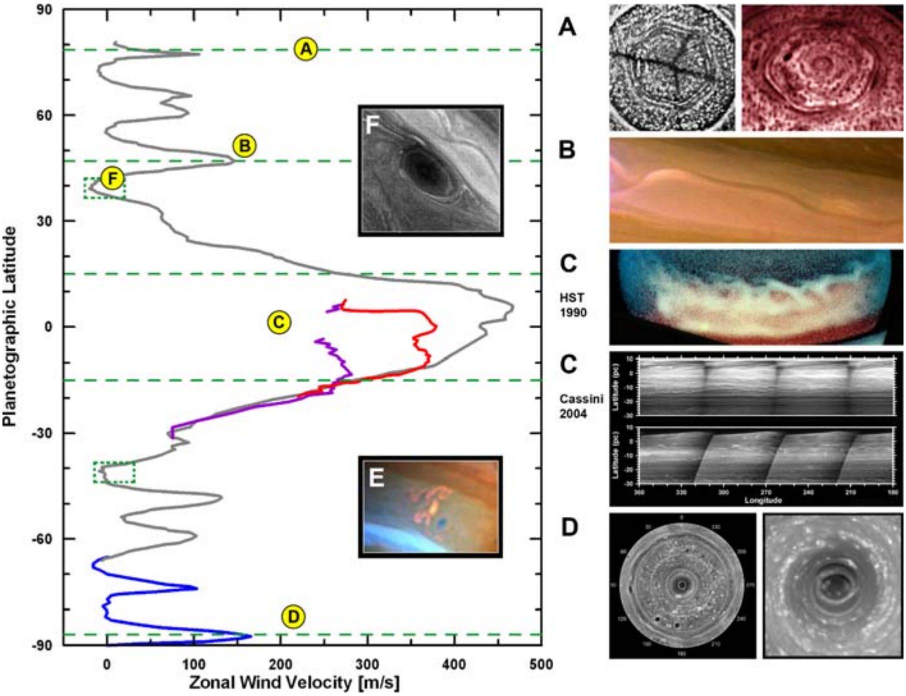

Fig. 5 General circulation of Saturn and relevant atmospheric features on its atmosphere. Winds at cloud level, relative to the interior reference frame measured by Voyager, traced by the Voyagers (*grey line*) and Cassini data of the Southernmost latitudes (*blue*) and equatorial region in different filters (*red* and *violet*). Relevant meteorological structures appear on the *insets*: **a** North polar hexagon in visible (Voyager 1) and infrared light (Cassini); **b** The Ribbon; **c** Saturn Great White Spot in the Equatorial Region in 1990 and the state of the equator as seen by Cassini in the methane absorption band and continuum filters; **d** The South Polar jet and the inner polar vortex; **e** Convective storms seen by Cassini; **f** Anticyclones from Voyager 1. The location of most convective storms appear marked with green dashed boxes

clouds and their temporal changes have been studied most recently by [35] and [36]. Related features are also seen at other levels from observations and retrievals of temperature and composition at infrared wavelengths [27]. The zonal jets are seen to extend into the stratosphere though decay with height [37]. Some eddy features are also evident at higher levels though some features such as Saturn's north polar hexagon seem to be confined to beneath the tropopause.

As with Jupiter, Saturn's cloud-level meteorology may extend much deeper into its convective interior than the shallow 'weather layer' within which the observed patterns of wind and clouds may be observed from space. Observational constraints on such (deep) atmospheric dynamics are very difficult to obtain, not least because of some fundamental 'degeneracies' in the near-surface signatures of deep and shallow circulations—i.e. very different processes (deep or shallow) may produce surface signatures that are more or less indistinguishable. A major objective of Kronos is therefore to obtain measurements that can resolve some of these ambiguities and ascertain which aspects of Saturn's meteorology and circulation are deep-seated and which are shallow.

As a first step, Kronos will obtain the first detailed in situ measurements of the vertical structure of Saturn's atmospheric temperature, winds, radiative balance and cloud structure, to depths of up to 10 bar where direct solar heating is essentially negligible. The factors determining the atmospheric thermal and density structure in the outer planets depend on a complex mix of radiative heating and cooling, turbulent convection (both 'moist' and 'dry') and larger scale circulation systems. The distribution of radiative heating in the upper troposphere is affected strongly by the presence of clouds and hazes, whose distribution is itself determined by the ambient circulation, and the concentration of various volatiles. Figure 5 shows a much simplified 'typical' vertical distribution of clouds, modeled by assuming a particular composition at depth and adiabatic uplift until different components become saturated and begin to condense. Such a distribution may reflect a global mean picture, but observations indicate considerable local variability.

Seasonal effects are also much stronger on Saturn than on Jupiter, and have a major impact on thermal structure in the stratosphere and upper troposphere. While Kronos will not monitor such effects directly, they will influence the state of the atmosphere at the time of its encounter with Saturn, and will provide information by comparison with earlier missions (such as Cassini). The nature and distribution of convection in Saturn's atmosphere is a major objective of the Kronos mission. It is now widely thought that convection, modified by the latent heat effects of water condensation and consequent changes in molecular weight, is a critical component of the tropospheric circulation of both the gas giant planets [38].

Moist convection is highly intermittent and leads to massive storm cells ~1000 km wide which carry water and other material vertically over ~3 scale heights (~75 km) into the upper troposphere. In ways that are still not fully understood, moist convection works rather differently from terrestrial storms, due to the very low mean molecular weight of the atmosphere. As on Jupiter [39], lightning may also accompany vigorous convection at times, though detection at Saturn in association with particular convective events has been more elusive [30].

The horizontal distribution of convection is also highly variable. Figure 6 shows a Cassini VIMS image of Saturn at 5 μm which reflects the distribution of clouds and convection at 2–4 bar. This indicates that convection (both dry and moist) is organized by the winds in the deep troposphere into zonal bands on a finer scale than at the top of the troposphere. This drastic change, evident in the meteorology between the visible face of Saturn and its expression at just 5 bar, is indicative of the changes in the driving forces as one delves deeper into Saturn. We expect that by directly sampling the internal structure down to 10 bar, below most of the direct radiative heating/cooling of the atmosphere, we will have a more direct picture of the processes controlling the dynamics in Saturn's atmosphere driven from deep inside the planet rather than from solar input/radiative cooling.

The primary goals of the meteorology and atmospheric dynamics investigation on Kronos will be to determine the nature of the deep circulation, differential rotation and convection in Saturn's atmosphere by combining observations from the Kronos probes with remote sensing measurements from the carrier spacecraft. For the probes, this will require in situ determination of vertical profiles of temperature, horizontal winds and cloud properties (aerosol particle densities, size distributions and composition, including possible chromophores) throughout the troposphere to a

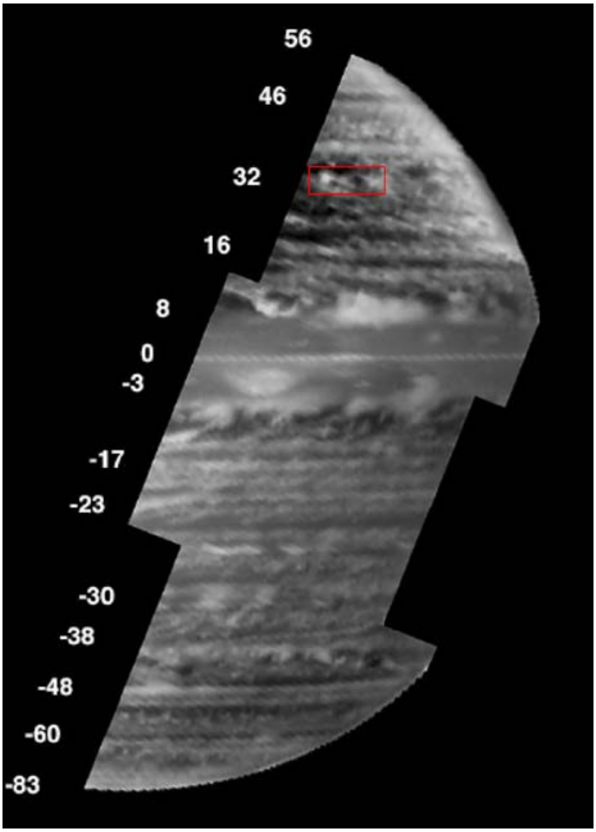

Fig. 6 Cassini VIMS image of Saturn at a wavelength of 5 μm [40, 41], showing cloud features and zonally banded structures at around 2–4 Bar. Here, the thermal image has been photometrically inverted to show high-opacity clouds as *white* and clearings in the deep cloud structure as *black*. This image mosaic reveals that, at depth, Saturn is an active, dynamic planet. *Bulky clouds near the equator* are likely convective in nature. At depth in mid and high latitudes Saturn exhibits a dense structure of alternating bands of clouds and clearings

pressure of up to 10 bar, at two dynamically distinct locations on Saturn. The profile of the water abundance will also be measured in order to constrain its role in moist convection processes. For the carrier, these goals will require measurements of temperature, deep cloud distributions, ammonia and water abundance distributions and deep winds, using a combination of near infrared and microwave radiometry, and gravity field measurements from a close periapsis pass.

2.3 Magnetic dynamo, magnetosphere and radiation environment

Like Jupiter, Saturn has a largely rotation-dominated planetary magnetosphere. But like Earth, solar wind convection and radial transport play major roles [42]. Understanding Saturn's magnetosphere (Fig. 7) will provide the "missing link" between the Jovian magnetosphere (then explored in-depth by Juno) and the Earth's magnetosphere (explored by many satellites).

The Kronos mission has the potential to resolve major open issues about Saturn's magnetic field, magnetic dynamo and internal rotation, its polar magnetosphere and radiation environment, and their couplings with the planet itself. Beyond planetology, redistribution of angular momentum via magnetic fields in astrophysical

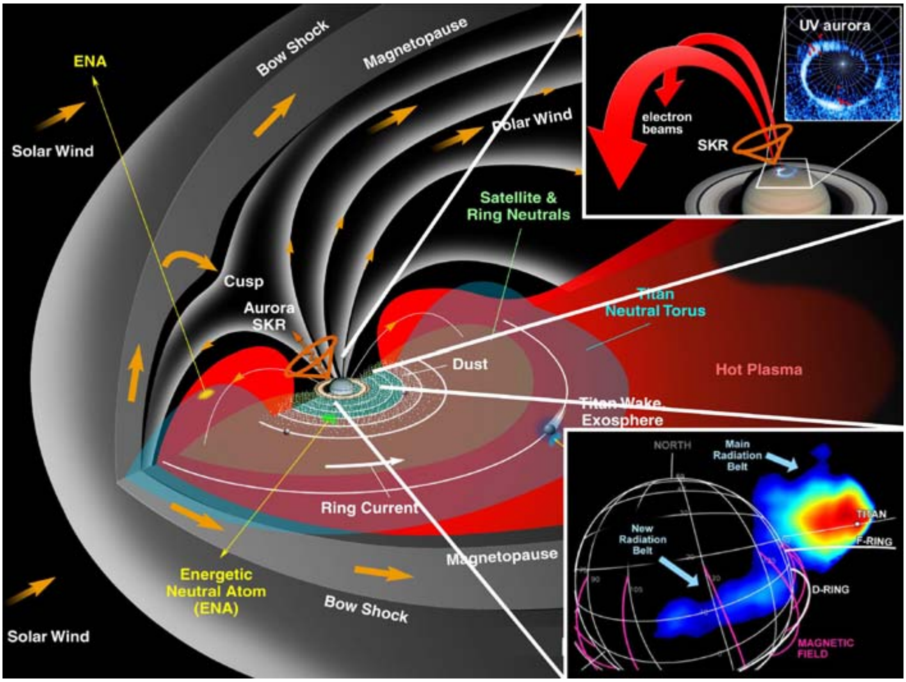

Fig. 7 *Saturn's magnetospheric regions and processes. Bottom inset* new radiation belt observed in ENA, *top inset* electron beams observed by Cassini and mapped to the aurora along field lines; auroral image by HST; orange cone sketches auroral (SKR) radio emissions

plasmas is a central question. Saturn's unique characteristics (neutral gas-dominated, dust-rich magnetosphere) make it an ideal model—better than Jupiter—for astrophysical situations such as the early phases of proto-star formation.

While all other magnetized planets in the Solar system have magnetic dipole axes tilted at an angle of 10° or more with respect to their rotation axes, Saturn's global magnetic field is almost perfectly axisymetric (angle of dipole tilt $\leq 0.7°$) [43], although a high-latitude 'anomaly' has been tentatively deduced from Saturn Kilometric Radiation (SKR) measurements [44]. Classical fluid dynamo theory [45] does not allow to maintain a field with perfect rotational symmetry, but new models do allow for the dipole tilt to be as small as 0.5°. Saturn's dynamo is thought to be produced by liquid 'metallic' hydrogen in its outer core, combined with strong convective motions and the rapid rotation of the planet itself (e.g. [46]). Accurate global field mapping is thus a key to both the composition and conductivity of Saturn's interior.

The Cassini spacecraft has already provided magnetometer measurements over several tens of close passes within $5R_S$ (average = $3.4R_S$) from Saturn's centre (R_{SS} = Saturn radius = 60,330 km). In addition the spacecraft made a closest approach at 1.33 R_S at the Saturn orbit insertion (SOI). Fluxgate magnetometer measurements near SOI suggested a possibly less symmetrical internal field within the radius of Saturn's D ring (1.11 R_S), as compared to the field model built from the more-distant periapses. Analysis is on-going, however further multiple passes and high-resolution scalar magnetometry at these very small distances—which are beyond the scope of Cassini's trajectory—are required to improve our knowledge of higher-order components or 'multipoles' of Saturn's field.

Another unique aspect of Saturn's magnetospheric field is related to the drifting rotational signatures of the azimuthal field and SKR. A mission such as Kronos, especially with an orbiter element, is expected to provide additional close-range (<1.3 R_S) magnetic data for Saturn, of great value for addressing the origin and nature of its 'rotational anomaly', and characterize the internal (Enceladus ?) [47] or external (solar wind ?) [25] control of the period variability, in order to determine Saturn's true internal rotation rate.

At Jupiter, the most dramatic signature of the planet-magnetosphere coupling and dynamics is the aurora (best observed in the UV), including the near polar signatures of the satellites-magnetosphere interaction. This coupling involves electric currents flowing along field lines, energetic particle acceleration, and associated plasma waves and radio waves. The latter permit remote sensing of the coupling variability as well as insights to the microphysics of the emission (electron distribution function tapped). Juno will significantly advance our understanding of Jupiter's polar magnetosphere via its polar orbit with low altitude perijove, allowing in situ measurements of fields, plasmas, currents, particles, at the key region where the magnetospheric activity is focused along converging magnetic field lines. Similar measurements should be performed at Saturn (top right inset of Fig. 7) to better understand the magnetosphere-planet coupling.

Finally, Kronos should provide new insights to the inner radiation belt discovered by Cassini inside the D ring [48].

2.4 Ring science

Whereas observed since the seventeenth century, Saturn's rings are still one of the most puzzling structures in our Solar System. To constrain the origin of the rings and their evolution, in situ observations are needed, following Cassini's success. In addition, Saturn's rings are the closest example of an astrophysical *disk*, one of the most fundamental structures in the Universe. The outer edge of the rings system (the A–F region) is located on the Roche limit itself, allowing for substantial accretion processes. The outer regions of the rings therefore share common properties with a protoplanetary disk.

The origin of Saturn's rings is still not understood. They were possibly formed by fragmentation of comets destroyed by tides after a too close passage [49] or by the destruction of an ancient satellite [50]. Our limited knowledge of the physical properties of the ring particles prevents us from discriminating these different scenarios. A key information would be the precise size distribution of ring particles down below the 10 cm scale. Direct observation of ring particles would allow us to achieve a major ring science objective: the physics of accretion (similar to planet formation). Despite the strong tidal field of Saturn, limited accretion is theoretically possible (e.g., [51]). Recent works show that moonlets and ringlets may be the two sides of a same object [51]. Cassini has recently provided new indirect proofs of this [52]). Direct observation of these aggregates would be valuable and would unveil a new class of Solar System objects: temporary moons. Thus, an exotic accretion physics could take place, resulting in the formation of temporary structures that need to be characterized in detail.

3 Mission profile

3.1 General mission architecture

The nominal mission includes two atmospheric probes delivered by a single carrier spacecraft. The primary science objectives of both elements is the formation of Saturn and the origin of its atmosphere. The probes enable in situ measurements of Saturn's atmosphere to be performed down to a pressure of 10 Bar. The carrier spacecraft is strongly inherited from Juno and enables a more global investigation of Saturn's atmospheric H_2O and NH_3, gravity and internal magnetic field, rings, and the inner magnetosphere.

3.2 Launcher requirements

Since Kronos was proposed as part of an international collaboration between ESA and NASA, the launch would have been possible with either a NASA or a European launch vehicle. Since the total mass of a flyby-based architecture with the two probes is estimated at less than 3000 kg, the projected launch vehicle for the mission could be an Atlas V-551.

3.3 Trajectory

Interplanetary trajectories to Saturn could be supported with chemical and/or solar electric propulsion (SEP) systems, combined with gravity assist at Earth and Venus, and for the relay trajectory architecture also at Jupiter. These trajectories result in flight times from ~6.3 years to ~17 years, although flight times over 12 years were found not desirable. Interplanetary and flyby/orbiter trajectory options are different for supporting relay or DTE architectures.

3.4 Direct to Earth communication

3.4.1 Flyby DTE trajectory

Using a direct-to-Earth (DTE) communication strategy decouples the probes from the carrier (after release) and thus allows for the most efficient, lowest cost and lowest risk mission architecture possible. This, of course, limits the data return from the probe mission, however, our preliminary analysis shows that the DTE capability meets the requirements for the Kronos mission. The probes are delivered on a Type II trajectory to Saturn to allow for probe entry at or near the sub-Earth point. Preliminary results suggest a longer flight time associated with DTE due to limits on the Jupiter gravity assist and to the probe entry geometry requirements. Preliminary launch characteristics for DTE and relay cases are shown in Tables 2 and 3.

Table 2 Preliminary launch characteristics for DTE option (shortest cruise for DTE)

EVVES case for DTE trajectory	
Launch vehicle	Atlas V-551
Departure condition	V_{inf}=4.1 km/s
Launch C3	C3=17 $\mathrm{km}^2/\mathrm{s}^2$
Launch mass	4,665 kg
Gravity assists	Earth–Venus–Venus–Earth
Arrival velocity	v_{inf}=5.8 km/s
Cruise time	11 years
Saturn arrival mass	3,345 kg
Mass post-SOI	2,721 kg
Sub-Earth point	~30° offset

3.4.2 DTE architecture

A relay architecture potentially provides the longest visibility between the probe and the carrier. This requires the relay spacecraft to be in a low inclination or equatorial orbit at a radial distance > 5 R_S. Zenith attenuation of radio signal is a function of probe depth, measured by atmospheric pressure. During the probe descent, the transmission of data must be performed in real time, with the data upload ending as the probe reaches its deepest point in Saturn's atmosphere. The preliminary DTE architecture includes a 200 MHz UHF link from the probes for direct-to-Earth communication to Earth, and an X-band link from the carrier for orbiter or flyby science and telemetry through the DSN. Data rate from the probe is the function of the antenna size, transmitter power, separation distance, and atmospheric conditions. Data compression potentially can increase the efficiency and thus the scientific return. Technology development in the areas of antenna design, telecom power, and frequency scanning and locking can vastly improve the expected performance. Preliminary analysis indicates that a data rate of ~60 bps from each probe is achievable without major new technology. This translates to a total data volume of

Table 3 Preliminary launch characteristics for relay options

Launch characteristics	
2015 EEJS Relay Trajectory	
Launch vehicle	Atlas V-551
Departure date	12/7/2015
Departure condition	V_{inf}=5.2 km/s
Launch C3	C3=29.5 $\mathrm{km}^2/\mathrm{s}^2$
Gravity assists	Earth–Earth–Jupiter
DSM	685 m/s
Arrival date	3/30/2022
Arrival velocity	v_{inf}=9.4 km/s
Cruise time	6.3 years
Dry mass	3,073 kg
Reference 2017 EEJS Relay Trajectory	
Launch year	January 2017
C3	C3=28 $\mathrm{km}^2/\mathrm{s}^2$
DSM	840 m/s
Arrival velocity	v_{inf}=5.8 km/s
Cruise time	7 years
Dry mass	2,935 kg

~0.44 Mb from the two probes. DTE potential at low frequencies (200–400 MHz) will be significantly (by an order of magnitude) improved with the next generation radio telescopes LOFAR (Low Frequency Array) and SKA (Square Kilometre Array.

Data link types on the relay architecture include: X-band telecom link for the carrier to the DSN; and 400 MHz UHF between the probes and relay spacecraft. Assuming a 400 K Saturn hot-body temperature noise at 400 MHz UHF frequency, and a corresponding 1.5 dB atmospheric attenuation at 10 Bar, the probes could support a data rate between of 512 bps, giving a total data volume of ~2 Mb from each probe.

On the carrier, the X-Band system uses ~35 W power and a 3 meter high gain antenna (HGA). Medium gain antenna and low gain antennas are likely necessary for maintaining links during cruise and safing scenarios. On the probes, the UHF LGA will work with an Electra transmitter at 20 W RF output. This requires an upgrade to the Electra transmitter, which currently operates at 12 W. Both ends of the radio link between the probes and the relay spacecraft must contain Ultra Stable Oscillators (USO) needed for radio interferometric (VLBI) and Doppler measurements (Doppler Wind Experiment -DWE- and Planetary Radio Interferometer and Doppler Experiment -PRIDE).

3.4.3 Ring science architecture

For the ring science purposes, we suggest an additional dedicated probe: Lora (Landers on Rings Array). Lora would not be a large probe, but rather a collection (2 to 3) of very small and simple probes, like "MicroProbes", containing only one efficient camera. The fleet of 2 to 3 identical probes would be dropped by Kronos during the flyby, and the probes would go directly into the rings at different locations, allowing to obtain high resolution images. One of the probes should target the ring plane, through a gap near a dense ring (B ring), in order to get information on the vertical structure of the ring.

3.5 Carrier

The spacecraft design is directly inherited from Juno replacing Juno's radiation vault mass with the probes. Juno is designed as an outer planet orbiter and already includes many of the components necessary to implement the mission. Low Intensity Low Temperature (LILT) solar panels from Juno and Bepi Colombo missions are baselined for Kronos, but require further tests for Saturn environment. The carrier is designed to deliver the probes to Saturn and to perform remote sensing measurement during its flyby. An orbiter configuration would include additional propellant tanks, and a modified power system to account for the higher power demands.

Structurally, the carrier consists of: (a) a spacecraft bus; (b) a propulsion system, including propellant tanks; (c) a power system, consisting of LILT solar arrays and batteries; (d) subsystems, including thermal management, CDH, GN&C, ACS, telecom; (e) and science instruments, including the MWR antennas. For the propulsion system both chemical and SEP were considered.

3.5.1 Carrier power system trades

At Saturn, the solar flux is about 15 W/m^2, or ~1% of that at Earth. Low Intensity Low Temperature (LILT) solar cells, developed by ESA for Rosetta, were tested up to ~70 W/m^2, while Juno's solar panels are designed to operate at Jupiter where the solar flux is ~55 W/m^2. New, high efficiency LILT cells could achieve a power output per unit area of 4 to 5 W/m^2, assuming a conversion efficiency of 30%. At this level of performance, according to a CNES study, a Juno-size solar panel could generate ~200 We, with the power system weighing ~300 kg (including batteries and conditioning system). Performance could be also increased with the development of concentrators.

Studies performed at both CNES and NASA [53, 54] demonstrated that short-lived missions could operate at Saturn using photovoltaic power generation. A flyby mission is expected to use batteries on both the probes and on the carrier spacecraft, and employ solar panels for backup only, in case not all data is transferred back to Earth in a single 8 hours telecom pass. For an orbiter mission the power requirement is expected to be continuous: near the periapsis the spacecraft would perform its science measurements, while during cruise to and from apoapsis it would perform data transfer to Earth, housekeeping, and recharge its batteries. This would have a significant impact of power system sizing. While solar power generation is expected to be the baseline configuration for the flyby architecture, future mission studies should also address the use of RPSs on an orbiter, in order to assess its impact on mission cost and architecture.

3.5.2 Saturn probes

Saturn's atmospheric circulation results in a distinct distribution of latitude bands and zones as seen most recently in the Cassini VIMS spectral data. Thus the Kronos mission should allow for the launch of two probes in different regions. The preliminary design calls for targeting one of the probes inside and one outside of the ±13° latitude band. Since the scale-height of Saturn is about twice that of Jupiter, it is not feasible for the probes to return data from the 50 to 100 Bar pressure levels—which would be required to measure the water abundance in situ—because of significant microwave absorption. Consequently, the probes will only be required to measure atmospheric composition and dynamics to about 10 Bar, while water and ammonia abundance will be measured using passive microwave radiometry from the carrier (like Juno) to 50–100 Bar.

The Saturn probes will use significant heritage from the Galileo probe (Fig. 8), including the thermal protection system (TPS), aeroshell design, and subsystems. Except for the TPS, heritage from the Huygens Titan probe will also prove extremely beneficial. Thanks to combined Huygens and Exomars, Europe has the technological background to provide for the Descent Modules of the two Kronos atmospheric probes. The gas giant-specific shield/aeroshell will be provided by NASA: its strong Galileo heritage will enable to get well-mastered interface specifications between the aeroshell and the descent module, and a controlled development. No development risk on US side is expected to be transferred to Europe's contribution, even via interface requirements.

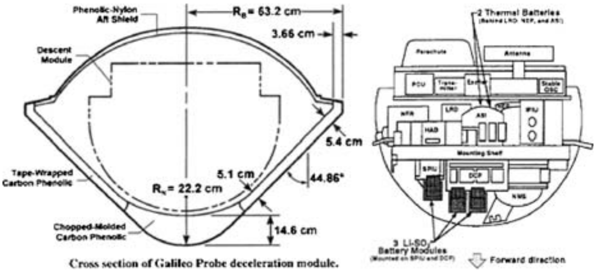

Fig. 8 Heritage Galileo descent module and probe (Galileo Probe Deceleration Module Final Report, Doc No. 84SDS2020, General Electric Re-entry Systems Operations, 1984; AIAA, “Project Galileo Mission and Spacecraft Design”, Proc. 21st Aerospace Science Meeting, Reno, NV, January 10–13, 1983; Proc. AIAA’83, 21st Aerospace Science Meeting, Jan. 10–13, 1983, Reno, NV)

The probes are considered autonomous objects, consisting of a set of science instruments, and subsystems. Each probe is housed inside a protective aeroshell. Its total mass of ~330 kg consists of a 222 kg deceleration module, and 117 kg descent module. The descent module houses the science instruments and subsystems, while the deceleration module includes the aeroshell, TPS, parachutes and separation hardware.

4 Instruments

4.1 Elemental and isotopic measurements of Saturn’s atmosphere

Saturn Probe measurements will be selected to meet the measurement requirements that address (1) theories of planetary origin and (2) fundamental knowledge of Saturn’s atmospheric structure and meteorological processes. The instrument complement will include a mass spectrometer for chemical and isotopic composition determination, an atmospheric structure experiment, a Doppler Wind Experiment for retrieval of a vertical profile of zonal winds, and a nephelometer to determine the structure of the atmosphere to at least 10 Bar and to obtain the radiative balance at this depth. The instruments baselined for the Kronos Probe investigation have a solid heritage from previous probe missions such as Galileo [55] (Fig. 9) and Cassini/Huygens [56].

4.2 Composition and isotopes

Light elements to be measured with an atmospheric probe mass spectrometer include H, C, N, S, P, Ge, As, and the noble gases He, Ne, Ar, Kr, and Xe. These measurements together with a determination of D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{3}He/^{4}He$, $^{20}Ne/^{22}Ne$, $^{38}Ar/^{36}Ar$, $^{36}Ar/^{40}Ar$, and the isotopic composition of Kr and Xe will provide a complete comparison with the Galileo Probe measurements at Jupiter and reveal key differences or similarities between these giant planets. However, we know that such a probe will not allow us to measure the deep, well-mixed abundance of oxygen, because of water condensation and meteorological processes. As the

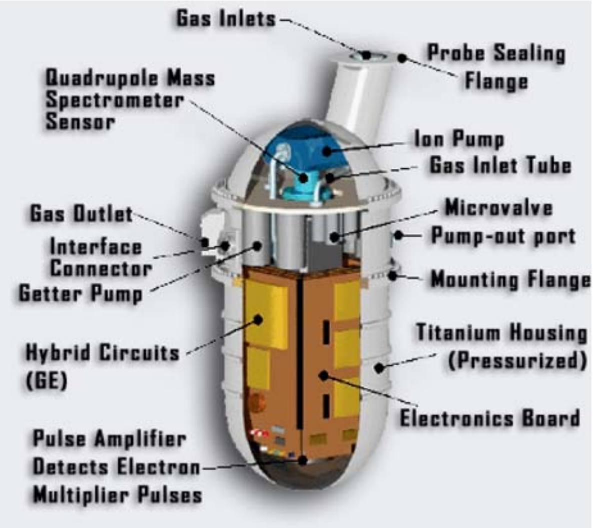

Fig. 9 The configuration of the Galileo Probe Mass Spectrometer (GPMS) that entered the Jupiter atmosphere on December 7, 1995 is shown. The Saturn Probe Gas Analysis Experiment will integrate several GPMS technologies with other advanced gas processing techniques to provide improved measurement sensitivity and precision at Saturn

abundance of oxygen in water is a key factor in the deduction of the composition and hence origin of giant planets, we propose to integrate on the orbital or flyby spacecraft a microwave sounder devoted to the remote sensing of water in the deep atmosphere of Saturn. Such an instrument is presently being developed for the Juno mission, to retrieve the O/H ratio in the deep troposphere of Jupiter.

Our present knowledge of the chemical and isotopic composition of the Jupiter and Saturn atmospheric chemical and isotopic composition is given in Table 4 together with the required precision of a Saturn Probe Gas Analysis System (GAS). The precisions listed represent a substantial improvement from the Galileo GPMS measurements. This performance will not only establish a full comparison with the Jupiter values, but will provide a robust data set for comparison with other planetary values. For example, differences in Xe isotopic fractionation between solar and meteoritic and between solar and terrestrial of <1% and <3% respectively per Dalton are resolvable with this precision. The static mass spectrometer design described

Table 4 SPMS measurement requirements

Elements	Jupiter/Sun	Saturn/Sun	KRONOS (%)	Isotopes	Jupiter	Saturn	Kronos (%)
He/H	0.81±0.02	~0.2	+1	D/H	$2.6\pm0.7\times10^{-5}$	$2.25\pm0.35\times10^{-5}$	<10
Ne/H	0.059±0.004	?	<5	^{3}He/^{4}He	$1.66\pm0.05\times10^{-4}$	?	<0.5
Ar/H	5.34±1.07	?	<5	^{13}C/^{12}C	0.0108±0.00005	0.011	<1
Kr/H	2.03±0.38	?	<25	^{15}N/^{14}N	$2.3\pm0.3\times10^{-3}$	?	<5
Xe/H	2.11±0.40	?	<25	Xe	<10% typical	?	<0.5
C/H	3.82±0.66	?	<10				
N/H	4.90±1.87	2–4 ?	<25				
S/H	2.88±0.69	?	<10				

Estimated Kronos precision might be higher or lower depending on abundances and measurement time during the descent spent on the species of interest. This will be explored in greater detail during the phase A study below enables these precisions. The Jovian elemental ratios of C/H, N/H, S/H, and D/H in this table were measured in the molecular species CH_4, NH_3, H_2S, and H_2 respectively. The GPMS made continuous direct measurements of gases ingested into the vacuum of the instrument in the 2–150 Dalton mass range during the descent except for short periods of time when processed gases were introduced into the mass spectrometer.

4.2.1 GAS specifications

The proposed Saturn Probe Gas Analysis System has a high heritage in both successful atmospheric probe composition/isotope investigations conducted at Jupiter [4, 55, 57] and Saturn's moon Titan [58]. Elements of the GAS designed to improve the precision of the measurements are adapted from in situ calibration, static mass spectrometry, gas separation, chemical processing techniques and advanced pumping systems developed for the Rosetta mass spectrometer Ptolemy [59] and presently under development for the 2009 Mars Science Laboratory [60]. The mass spectrometer is a quadrupole mass spectrometer similar to more than a dozen that have been developed at the NASA Goddard Space Flight Center and successfully operated in the upper atmosphere of the Earth and Venus.

4.2.2 Noble gas enrichment and static mass spectrometry

The combination of a noble gas enrichment system, a gas scrubber that can remove all chemically active gases, a chemical getter pump in the MS analyzer region, and a high conductance valve between the MS and the WRP will enable static MS operations for higher precision noble gas measurements than were possible at Jupiter with the GPMS. The static measurements interrupt direct sampling of the atmosphere for a portion of the descent, but are necessary to obtain the desired precision. The noble gas enrichment system was proven on the Galileo Probe MS and consists of chemical getters and traps that can enrich the trace noble gases Kr and Xe. The Galileo Probe noble gas enrichment system was able to provide measurements to the sub ppb levels for isotopes of Jovian Xe.

4.2.3 Nitrogen combustion for $^{15}N/^{14}N$ isotope measurement

The $^{15}N/^{14}N$ ration on Jupiter was obtained from the NH_3^{++} signal at 8.5 and 9 Dalton for the two nitrogen isotopes. Due to the difficulty of removal of spectral interferences in this approach we provide an NH_3 oxidation reactor on GAS to produce N_2 so that this measurement can be carried out with higher precision. This element of GAS could be developed using techniques similar to those developed for Rosetta and Beagle 2, and expertise and techniques developed for the analysis of solar wind nitrogen implanted in the GENESIS targets.

4.3 Meteorology and atmospheric dynamics

In situ measurements that address the meteorology and atmospheric dynamics goals of the Kronos mission include density, pressure and temperature sounding to characterize the atmospheric structure and instruments to measure the radiative balance, cloud structure, and zonal winds also down to a pressure of 10 Bar.

4.4 Measurements achieved with a Saturn probe nephelometer

The composition and precise location of cloud layers in Saturn are largely unknown. They may be composed of ammonia, ammonium hydrosulfide, or simply water. Because of this relative paucity of information on Saturn's clouds, the demands we place on a cloud particle sensor (nephelometer) are significant.

For Kronos, we have baselined a new instrument which would measure not only the amplitude phase function of the light scattered by the clouds from a laser source on the probe, but also the polarization ratio phase function as well. It does this at two wavelengths, separated by about an octave in wavelength near 1 μm. The phase functions are sampled at six discrete angles, chosen to maximize their leverage in distinguishing between different size, shape and aerosols compositions. These measurements at an optical depth unity as long as ~10 km permit to determine the aerosol number density, their particle size, an indication of the particle shape, and the particle's index of refraction at the two wavelength, which may be used to infer the molecular constituency of the aerosols.

4.5 Atmospheric structure instrument

The Kronos Atmospheric Structure Instrument (ASI) consists of three primary sensor packages: (1) a three axial accelerometer (ASI-ACC), (2) a pressure profile instrument (ASI-PPI), (3) temperature sensors (ASI-TEM). The proposed instrument will benefit from a strong heritage of the Huygens ASI experiment of the Cassini/Huygens mission [61]. The key in situ measurements will be atmospheric density, pressure and temperature profile by measuring deceleration of the entry vehicle and performing direct temperature and pressure measurements during the descent phase. The ASI-ACC will start to operate since the beginning of the entry phase, sensing the atmospheric drag experienced by the entry vehicle. Direct pressure and temperature measurements will be performed by the sensors having access to the atmospheric flow from the earliest portion of the descent until the end of the probe mission at approximately 10 Bar.

4.6 Measurements with a Doppler wind experiment

The primary goal of the Kronos Doppler Wind Experiment (DWE) is to measure a vertical profile of the zonal (east–west) winds along the probe descent path [62]. A secondary goal of the DWE is to detect, characterize, and quantify microstructure in the probe descent dynamics, including probe spin, swing, aerodynamic buffeting and atmospheric turbulence, and to detect regions of wind shear and atmospheric wave phenomena. The Kronos Doppler Wind Experiment (DWE) can be designed to work with a probe DTE architecture or a probe-to-relay architecture. Both options include USO requirements and differ only in the angle of entry and DTE geometry requirements (see Mission Design). For relay, the system comprises a probe and a carrier ultrastable oscillator (USO) as part of the probe/carrier communication package. Involvement of several observing telescopes in interferometric mode (PRIDE) will significantly improve the accuracy and robustness of the measurements. The proposed experiment benefits from the strong heritage of both the Galileo and Huygens doppler wind experiments [63].

4.7 Instruments on the carrier spacecraft

Further definition of the carrier spacecraft will take place during the Kronos Phase A study. This may be a flyby spacecraft or a Saturn orbiter. Definition of the orbital instruments will also take place during this period. A key objective of the payload on the carrier spacecraft will be to secure deep, global abundances of H_2O and NH_3 and their distributions over al latitudes using microwave radiometry. The technology to implement these measurements is mature through the radiometers developed for the Juno mission. The mission objectives for the orbiter/flyby spacecraft are inherited from the Juno mission and include;

- Measurements of the global oxygen (water) and nitrogen (ammonia) abundances.
- Measurements of Saturn's internal mass distribution (core mass) via gravity science
- Measurements of Saturn's internal rotation and convection (whether Saturn rotates as a solid body) via gravity science (determination of high order gravitational moments; see)
- Measurements of Saturn's internal magnetic field sufficient to investigate the source location of the field.
- Measurements of the properties of Saturn's innermost magnetosphere (inner radiation belt, possible ring-associated currents, UV/IR/radio auroras, magnetic anomalies)
- Measurements of the deep atmospheric structure and dynamics via microwave sounding

4.7.1 Multi-frequency microwave radiometry

The design of the microwave radiometers will follow closely the Juno design, with the exceptions that the measurement at Saturn is considerably less driving. Without the strong synchrotron emission from Jupiter, the measurement noise will be less and thus the instrument design less complicated (beam pattern, etc.). Furthermore, the selection of wavelengths (frequencies) will be tuned to the Saturn atmosphere. As with Juno, it is expected that the radiometers will be a set (approximately 6) of frequencies ranging from 1 cm to 100 cm. Having the full latitude coverage is essential for understanding the roles of ammonia and water in Jovian meteorology and for placing the probe measurements in context.

4.7.2 X/Ka band up/downlink system for gravity science

Most of the uncertainty in our knowledge of Saturn's core stems from uncertainties in the equation of state and the gravity zonal harmonics $J4$ and $J6$ and to limited knowledge of how Saturn's deep interior rotates. Current uncertainties are 1% in $J4$

and 30% in *J6*. Kronos improves the knowledge of *J4* and *J6* by over 3 orders of magnitude (*J4* ~10 ppm accuracy, *J6* ~100 ppm accuracy). This removes the uncertainty regarding interior rotation and estimates the abundance of water, reducing the core mass uncertainty and total mass of heavy elements to a few Earth masses.

Using an existing Linear Ion Trap (LITS) as frequency reference (or an improved follow on) a DSN ground station (DSS25) transmits X and Ka-band radio signals to the spacecraft, then receives the transponded signals and very accurately measures their frequencies. Simultaneously, water vapor radiometers (WVR) at the DSN station measure Earth-atmospheric brightness temperatures in the direction of the antenna beam, thereby determining the zenith signal delay caused by the wet component of the troposphere, and ultimately the tropospheric correction (refraction) to the raw Doppler data. The same set of on-board instrumentation on the carrier spacecraft will enable multi-disciplinary VLBI tracking experiments with ultra-precise characterization of the state vector of the spacecraft, reaching tens of meters in the lateral direction.

4.7.3 Vector magnetometer

The instrument must be of sufficient sensitivity to measure perturbations caused by field aligned currents. The successful operation of the Cassini fluxgate magnetometer at Saturn makes it a natural candidate for inheritance for the design of the Kronos magnetometers. The new generation of digital fluxgate sensors have masses of the order ~200 g, and therefore make very little demand on overall payload mass. For a Cassini-like configuration, each sensor would be capable of measuring fields up to ~44.000 nT, well below the atmospheric depths at which the Kronos probes would be expected to operate.

4.7.4 Plasmas sensor

The instrument must quickly measure electron and ion energy angular distributions (100 eV–20 keV) from an effectively non-rotating platform.

4.7.5 Energetic particle sensor

This instrument must operate at the higher energies (20 keV—several MeV) while the plasma sensor functions at lower energies. Although a 1 MeV upper limit is sufficient to address magnetosphere–ionosphere coupling issues, higher energies (up to 30–50 MeV) are needed to study the radiation belts. In situ study of the new radiation belt seen by Cassini-MIMI inside the D-ring, would require a small ride-along particle detector on the probe itself. Such a sensor was carried by Galileo probe.

4.7.6 Plasma and radio wave receivers

Cassini and Stereo spacecraft carry radio and plasma waves spectro-polarimeters which can be programmed to operate according to very diverse setups (spectral and temporal resolutions, snapshots or surveys, waveform capture, polarization measurement, etc.). In addition, they have goniometric capabilities, i.e. they enable the instantaneous determination of the direction of the brightest point source at each measurement, and thus the possibility to synthesize images of the radio-sources. The next generation of these radio spectro-goniopolarimeters has been miniaturized and could be implemented for resources of ~1 kg and ~1 W using development heritage from e.g. BepiColombo/MMO.

4.8 The Lora (Landers On Rings Array) MicroProbes

All the ring science objectives can be met by two to three very simple probes (MicroProbes), whose sole payload would be a high-resolution camera, dropped in different locations of the rings (A, B, C by order of priority). The only limit to the resolution is the time for data transfer before impacting into the rings. A Ritchey–Chretien reflector, with 1m focal length and diffraction limited at 5×10^{-6} rad (≥ a 15 cm diameter) would be suited. As the probes get closer to the ring, the resolution increases and allows to achieve the ring science objectives.

A low inclination impact angle is preferred (~1°), its feasibility depending on the arrival trajectory of the Kronos spacecraft. A high resolution imager for ring science that gives the required <1–10 m resolution images requires narrow angle cameras on the Lora probes that will be evaluated in the Kronos Phase A study. An example of synthetic images of A ring wakes at different resolution is shown in Fig. 10. Assuming a resolution of 6×10^{-6} radians/pixel (like the Cassini ISS-NAC), the minimal distance of approach to achieve a given resolution is given in Table 5.

The maximum scientific return is expected when the distance to the rings is <100 km. However, once the Lora probes are below 8,000 km, they could achieve a better resolution than the best Cassini images.

In order to stabilize and orient the spacecraft to allow a good pointing, a set of reactions wheels and gyros onboard are necessary. The small inertia of the probes may allow easy re-orientation during the descent.

4.8.1 Timeline for the Lora probe

In the current state of the design of the Kronos mission, the exact trajectory of the Lora probe has not been precisely determined. We assume below that the Lora Probe would be launched on an hyperbolic trajectory, with a ~1° inclination above the ring

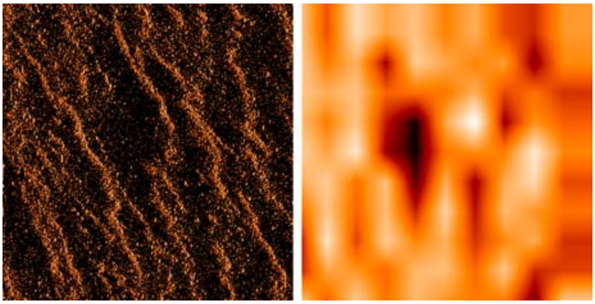

Fig. 10 Synthetic images of A ring wakes at 60 m resolution (*left*) and 60 resolution (*right*) (H. Salo)

Table 5 Ring science operations

Altitude above rings (km)	Resolution (m/pixel)	Science objective
2,000	10	Microstructure/aggregates
200	1	Ring thickness
20	0.1	Particle size distribution

plane, with nodes located around 10^5 km from Saturn's center. The velocity in the Saturn's inertial frame would be about ~ 27 km/s. With this approach geometry, the resulting timeline for the Lora probe is presented in Table 6.

During its descent to the ring plane, the Lora probe would transmit the collected data as soon as they are collected (in the spirit of what was done for the Huygens descent on Titan), because of the possible destruction of the probe during its crossing of the ring plane. If the Lora probe survives the ring-plane crossing, then new data could be collected and transmitted again to the Kronos spacecraft.

Since the Lora probe is meant to be a "microprobe" (i.e. with a single instrument and a simple communication system) its communication package would be designed primarily for communicating with the Kronos spacecraft only, which would record and transmit the data to Earth.

4.9 Saturn atmosphere wind diagnostics by means of radio measurements of the probe motion (PRIDE)

This experiment does not require special on-board instrumentation and can be conducted with radio signals in both communication scenarios, DTE and probe-to-carrier relay. In particular, it will provide additional input into measurements of the wind profile not requiring an a priori assumption on a one-dimensional model of the wind.

DTE could be used for additional measurements by determining an additional component of the probe's state vector. Indeed there is no need to limit the experiment to zonal component measurements since a meridional component could be measured as well. Even 3D diagnostics of the motion are not out of the question, i.e. the descent velocity can be included in the set of measured values from the experiment. To what extent the measured motion of the probe represents the wind depends on specifics of the atmosphere flight. A combination of Doppler and interferometric measurements can provide unambiguous determination of the descent trajectory—coordinates and their (at least first) derivatives.

Table 6 Timeline for the Lora probe

Time before impact (or ring-plane crossing)	Altitude above rings (km)	Resolution (m/pixel)	Science Objective
−1 h 9 min 21 s	2,000	10	Microstructure/aggregates
−6 min 56 s	200	1	Ring thickness
−41 s	20	0.1	Particle size distribution

5 Conclusions and summary

Multiple probes to the giant planets are critical for collecting the data required for understanding the formation of our solar system, and by extension, of extrasolar systems. Indeed, our giant planets can be studied in much finer detail than any exoplanet ever will, and they have preserved chemical and isotopic relics of early solar system reservoirs. In exploring the composition of Saturn with Kronos, we shall go back to the times when a tiny fraction of a molecular cloud collapsed to give birth to a special stellar system: the Sun and its planets. The probes will allow an in-depth exploration of Saturn and its comparison with results obtained by the Galileo mission at Jupiter. This comparison between the two most massive planets of the Solar System is a prerequisite to a detailed understanding of the origins of the Solar System. Kronos shall also investigate Saturn's complex atmospheric dynamics, which is a fantastic laboratory for this field of research. It will measure the planet's magnetic field very close to the planet's atmosphere and thus unfiltered by the rings, with direct consequences for understanding the planet's dynamo and deep rotation. Kronos also provides a possibility to study Saturn's rings in fine details. Altogether, through innovative approaches this international mission allows a combination of essential measurements that concern the ringed planet but impact many disciplines and the understanding of our origins.

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