Canadian radiation belt science in the ILWS era

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Abstract. The Outer Radiation Belt Injection, Transport, Acceleration, and Loss Satellite (ORBITALS) is a Canadian Space Agency small satellite mission proposed as a Canadian contribution to the satellite infrastructure for the International Living With a Star (ILWS) program. Planned to operate contemporaneously with the NASA Radiation Belt Storm Probes (RBSP), the ORBITALS will monitor the energetic electron and ion populations in the inner magnetosphere across a wide range of energies (keV to tens of MeV) as well as the dynamic electric and magnetic fields, waves, and cold plasma environment which govern the injection, transport, acceleration and loss of these energetic and space weather critical particle populations in the inner magnetosphere. Currently in Phase A Design Study, the ORBITALS will be launched into a low-inclination GTO-like orbit which every second orbit maximizes the long lasting apogee-pass conjunctions with both the ground-based instruments of the Canadian Geospace Monitoring (CGSM) array as well as with the GOES East and West and geosynchronous communications satellites in the North American sector. In a twelve-hour orbit, every second apogee will conjunct with instrumentation 180 degree in longitude away in the Asian sector. Specifically, the ORBITALS will make the measurements necessary to reach reveal fundamental new understanding of the relative importance of different physical processes (for example VLF verses ULF waves) which shape the energetic particle populations in the inner magnetosphere, as well as providing the raw radiation measurements at MEO altitudes necessary for the development of the next-generation of radiation belt specification models. On-board experiments will also monitor the dose, single event upset, and deep-dielectric charging responses of electronic components on-orbit. Supporting ground-based measurements of ULF and higher frequency wave fields from the Canadian CARISMA (www.carisma.ca) magnetometer array, as well as from other distributed networks of ground-based instrumentation will also be critical for reaching science closure. This paper outlines the radiation belt science targets for the ORBITALS mission, and describe how the ORBITALS can provide an essential complement to other proposed inner magnetospheric missions in the ILWS era.

Index Terms. ILWS, inner magnetosphere, magnetic storms, radiation belts.

1. Introduction

Recent international attention has focused on understanding the dynamics of the outer electron radiation belt, and this will represent a high priority for the International Living with a Star (ILWS) program. The dynamics of MeV energy electrons in the outer radiation belt have been implicated in the generation of rogue commands, and in some cases total failures, of Earth orbiting satellites principally through deep dielectric charging (e.g., Baker et al., 1998; Baker, 2002). The technological importance of the space weather effects of these so-called satellite "killer electrons" has lead to a significant effort to understand the physics behind radiation belt particle acceleration and loss, with the ultimate goal of producing physics-based now- and fore-casting models, as well as revised radiation belt specification models for the aerospace industry (see, e.g., the recent paper by O'Brien (2005) as well as the efforts by the COSPAR Panel on Radiation Belt Environment Modeling (PRBEM; see e.g., http://www.cosparhq.org/scistr/prbem.htm).

Two important Canadian Space Agency (CSA) assets for ILWS are its small satellite program, and the ground-based Canadian Geospace Monitoring (CGSM; see www.cgsm.ca) program. In respect of the radiation belts, following a successful concept study, the CSA has now approved a Phase A study for the Outer Radiation Belt Injection, Transport, Acceleration and Loss Satellite (ORBITALS; www.orbitals.org), a small satellite mission to the inner magnetosphere and the radiation belts proposed for launch in 2011-12 (see Mann et al., 2006, for more details).

In this paper we outline Canadian plans to provide experimental infrastructure which will support radiation belt science during ILWS (see also Liu et al., 2005). We discuss the outstanding science questions which will need to be addressed to understand radiation belt dynamics, and outline how ground- and satellite Canadian infrastructure to be developed and deployed during ILWS will enable the question of why such an apparently quiescent object as the Earth's magnetosphere can act as such an efficient acceleration of electrons to relativistic energies in the Van Allen belts.

2. Radiation belt dynamics

The radiation belts are typically separated into inner and outer zones, separated by the slot region which is typically devoid of MeV energy particles. The inner zone is typically less dynamic that the outer zone, the latter spanning L-shells from around L ~ 2.5 to L ~ 6. Outer zone electron fluxes can vary by several orders of magnitude on timescales from minutes, to hours, months, and years, and the response is energy dependent. As shown in Fig. 1, there is also significant global coherence across L-shells in all energies.

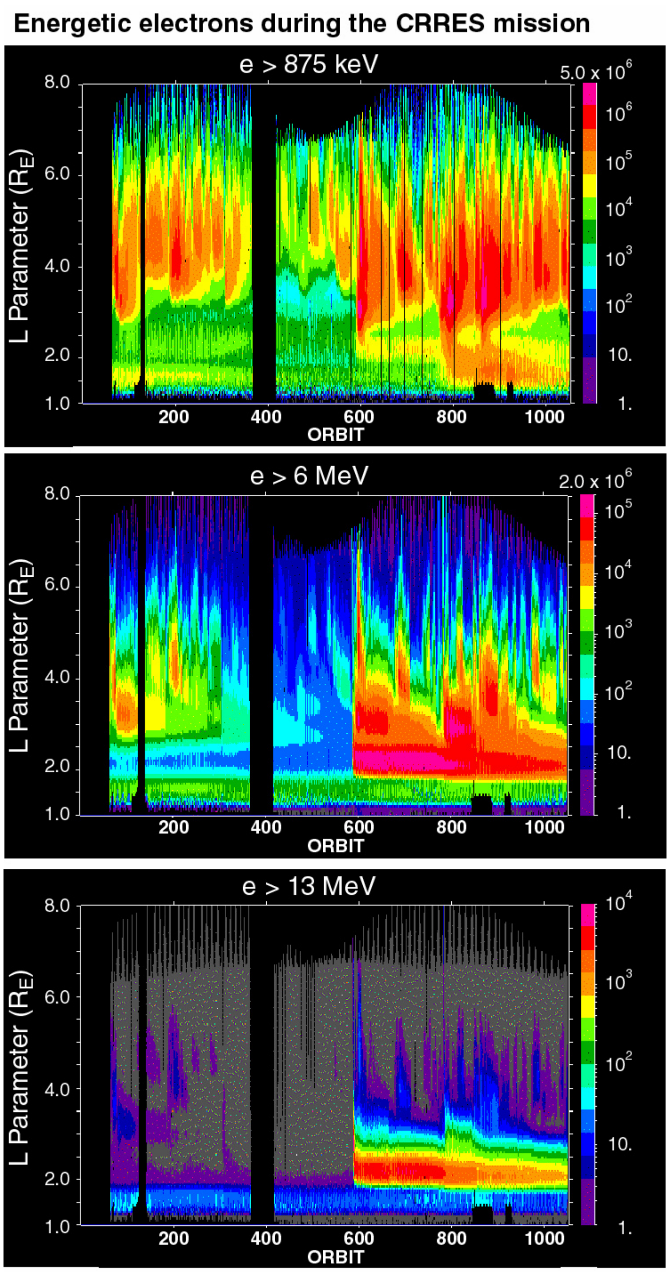

Fig. 1. Radiation belt electron dynamics as monitored by the CRRES satellite during the course of its mission life in the >875 keV, > 6 MeV, and > 13 MeV energy channels (from Mann et al., 2006).

Fig. 1 shows the dynamics of electron radiation belts as measured by the CRRES spacecraft during its 15 months of operation. The slot region is clearly visible, with the outer zone showing its variability in flux as inwards and outwards penetration on a range of timescales. Also clearly shown are aperiodic intervals of slot filling events, including that following the March 24, 1991 storm (around orbit 600) where the propagation of a shock front through the magnetosphere transported and accelerated electrons into the inner magnetosphere and created a new population of very energetic electrons in the inner zone. The L-value of the inner edge, as well as the peak in radiation belt flux, are also known to be strongly correlated with Dst, higher Dst leading to deeper penetration of the radiation belts (e.g. Tversyka et al., 1986).

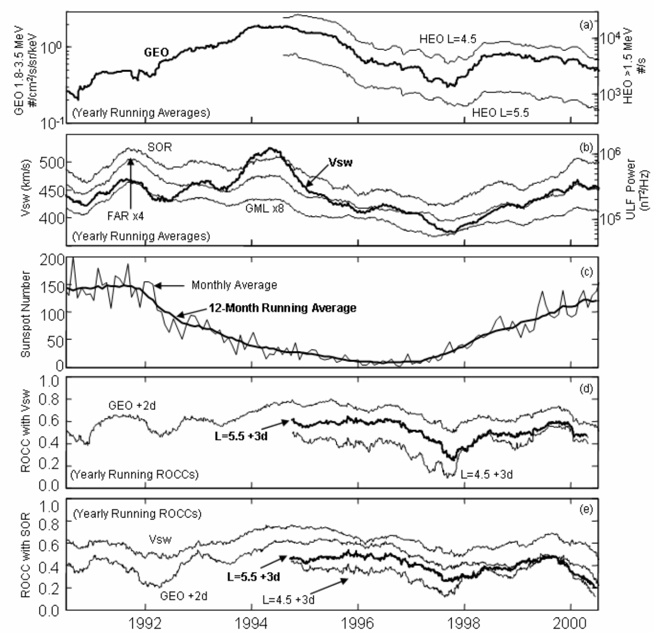

Fig. 2. Yearly running averages of (a) 1.8-3.5 MeV electron flux from LANL at GEO, and from HEO at L=4.5 and L=5.5; (b) Vsw and ground-based ULF wave power; (c) Sunspot number; (d) ROCC of 1.8-3.5 MeV electron flux with Vsw, and (e) with ULF wave power from 1990-2001 (from Mann et al., 2004).

The outer zone electron flux is known to be well-correlated with periods of enhanced solar wind speed (e.g., Paulikas and Blake, 1973), this trend being clearly seen in the first two panels of Fig. 2 which shows yearly averaged data from almost a solar cycle. This is especially true during the declining phase of the solar cycle (e.g., Rostoker et al., 1998; Mathie and Mann, 2000) where periodic enhancements in the outer zone flux can occur every 27 days in the Earths frame as a result of encountering fast solar wind streams emanating from trans-equatorial solar coronal holes. Similarly, aperiodic interplanetary coronal mass ejections (ICMEs) can cause enhancements in the outer zone flux. The variability in the outer zone variations at solar maximum is somewhat less well-correlated with solar wind speed (Vsw), which is likely related to the effects of the ICMEs. Both of these features can also be seen in the yearly running rank order correlation coefficients between daily Vsw (solid line panel (b)) and electron fluxes (panel (a)) shown in panel (d) of Fig. 2. Note that the electron fluxes are lagged with respect to Vsw to reflect the maximum 2 to 3 day lag in Vsw-MeV electron flux correlation (see Mann et al., 2004 for more details). Fig. 2 further illustrates that the relativistic electron flux variability across the outer radiation belts demonstrates a “remarkable” global coherence across the entire outer zone especially in the declining phase (see also, e.g., Kanekal et al., 2001).

Following the onset of any given storm there is typically a sharp reduction in the flux in the outer zone. This could be as a result of magnetopause shadowing, from wave-particle losses to the ionosphere in VLF/ELF whistler mode chorus waves, or EMIC waves, or due to adiabatic temporal changes due for example to outwards adiabatic electron motion due to main phase magnetic field reductions (the so-called “Dst-effect”). Over the course of 1-2 days during the storm recovery phase the flux tends to partially or completely recover, and in some cases the flux increases above pre-storm levels. While there is a definite correlation between radiation belt flux changes and the occurrence of geomagnetic storms as defined by Dst, only around 50% of storms produce overall flux rises, and whether a flux rise occurs is essentially uncorrelated with Dst (Reeves et al., 2003). However, the location of the peak in radiation belt flux (O’Brien et al., 2003, Tverskya, 1986) of the electron radiation belt is well-correlated with Dst. Larger Dst storms tend to produce a flux peak and an inner edge which are located at lower-L. Recent results have shown that the loss processes have a strong local time dependence (e.g., Green et al., 2004). EMIC waves are a promising candidate as the dominant loss mechanism, however more studies are needed.

It appears that the outer radiation belt electron flux response occurs as a result of “delicate balance” between acceleration and loss processes (e.g., Friedel et al., 2002; Reeves et al., 2003; Summers et al., 2004). There are at least 9 (e.g., Friedel et al., 2002) proposed acceleration mechanisms, the most popular invoking wave-particle interactions with a range of candidate wave accelerators. A significant amount of recent attention has focused on two competing wave theories: those which violate the first invariant, such as interaction with ELF/VLF waves (e.g., Horne et al., 2005, and references therein), and those which violate the third invariant, such as radial diffusion perhaps enhanced through the interaction with ULF waves (e.g., Elkington et al., 2003) or through other ULF wave transport processes (e.g., Liu et al., 1999; Summers and Ma, 2000).

Radiation belt electron flux at geosynchronous (GEO) is better correlated with ULF wave power than any other geomagnetic indicator or index (e.g., O’Brien et al., 2001). Moreover, the response in the inner magnetosphere between GEO and L=4.5, as determined from the LANL and HEO satellites, shows that solar wind speed correlated radiation belt flux enhancements peak first at GEO, followed by L=5.5, and then L=4.5 (Mann et al., 2004).

This inwards transport of information, and most likely also radiation belt flux, is consistent with an inwards radial transport process such as ULF wave radial diffusion. Fig. 2 (panels (d) and (e)), illustrates the interesting fact that the yearly averaged daily MeV energy electron flux is better correlated with Vsw than ULF wave power as determined from ground-based magnetometers. This could be due to ionospheric screening of some important ULF wave power, such as higher azimuthal wavenumber or narrower latitudinal width components, or could be indicative of the likely additional importance of other Vsw correlated acceleration processes which operate to in addition to ULF waves. Higher-L fluxes are also better correlated with both Vsw and ULF wave power. However, these is no doubt as is shown clearly in panels (d) and (e) of Fig. 2 that there is a very close correspondence between MeV electron flux across the entire outer zone, and both Vsw and ULF wave power. In the rising phase, this correlation increases at the lowest-L. Importantly, the correlations suggest that the response of the radiation belts is different during the declining and rising phases of the solar cycle, implying that the relative importance of different mechanisms is changed, or that how these processes impact the radiation belts is different at lower-L during the rising phase.

Fig. 2 emphasizes and summaries the relationship of radiation belt flux relationship to solar wind speed and to ground-based measurements of ULF wave power. There is also certainly strong evidence that ELF/VLF wave power is also enhanced during a number of radiation belt geoeffective storms (e.g., Meredith et al., 2003; Horne et al., 2005), and studies examining local electron phase space density profiles have found some evidence of the growth of local peaks in PSD which cannot easily be explained by radial diffusion (e.g., Green and Kivelson, 2004). Indeed, studies which have used both ground-based ULF wave power, as well as a microburst proxy for VLF wave power, have found evidence in support of dual acceleration whereby both the ELF/VLF and the ULF processes might both be statistically important in driving overall radiation belt dynamics (e.g., O’Brien et al., 2003). Hence it seems likely that the hypothesized ELF/VLF processes may also be important. However, the relative importance of processes such as ELF/VLF and ULF wave acceleration remains poorly defined.

Case and statistical studies using currently available data have generated evidence in support of a number of different acceleration and loss processes. However, which processes dominate and under what conditions is not clear. Further progress requires a definitive characterization of the waves and their causal effects; in-situ wave, fields and plasma measurements in the equatorial outer zone radiation belt being crucial. In combination with modeling, such global scale in-situ measurements would have the potential to enable science closure in respect of determining the dominant acceleration and loss processes which are responsible for determining the structure and dynamics of the outer radiation belt.

3. ILWS missions to the radiation belts

The inner magnetosphere has been severely under-explored by previous satellite missions, and understanding the dynamics of the inner magnetosphere (which some have called the "ignorosphere") remains one of the major challenges in geospace and will form an important focus for ILWS. Specifically, the answer to the question of what accelerates particles in the Van Allen belts has remained elusive since its discovery around 40 years ago.

The International Living with a Star (ILWS) program has adopted "Mission" and "Objectives" statements within its Charter (see http://sec.gsfc.nasa.gov/ilws/ilws_charter.htm): **ILWS Mission:** Stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity.
ILWS Objectives: To stimulate and facilitate: 1) Study of the Sun-Earth connected system and the effects which influence life and society, 2) Collaboration among potential partners in solar-terrestrial space missions, 3) Synergistic coordination of international research in solar-terrestrial studies, including all relevant data sources as well as theory and modeling, 4) Effective and user driven access to all data, results, and value-added products.

NASA has now approved its two spacecraft Radiation Belt Storm Probes (RBSP) mission as part of its Living with a Star (LWS) program; LWS being one of the major US contributions to ILWS. The highest priority LWS Geospace science target is to examine the "Dynamics of the Near-Earth Radiation Environment". Specifically, the objectives towards this goal include to: i) "Discover the processes that accelerate, transport and distribute energetic particles during geomagnetic storms", and ii) "Understand and predict the intensity of outer-zone electrons due to high-speed solar wind streams". To meet these objectives, measurements are targeted at "(1) ions and electrons over a broad range of energies; (2) magnetic fields; (3) electric fields; and (4) ULF and VLF waves" (see for example http://lws.gsfc.nasa.gov/docs/Geospace/GMDTReportforWeb.pdf, the report of the LWS Geospace Mission Definition Team (GMDT), Sept 2002). The LWS GMDT identified that these measurements were needed in "near-equatorial elliptical orbits with multiple, simultaneous measurements at different radii", and that "GTO are a likely candidate with excellent partnering possibilities" (see the LWS Science Architecture Team Report to NASA SECAS (Sun-Earth Connections Advisory Committee), August 30th 2001). In recognition of the importance of the global coverage from additional inner magnetospheric satellites operating contemporaneously with RBSP, the LWS Management Operations Working Group (MOWG) further encouraged NASA to seek network level collaborations with international agencies to achieve this goal in a letter to NASA Headquarters on July 2nd 2003.

The ILWS program offers an ideal opportunity to co-ordinate radiation belt missions from partner agencies, in perfect alignment with the ILWS charter. To this end, the ILWS Magnetosphere Task Group gave "high priority" to "an inner magnetospheric fleet of a minimum of 3 satellites on GTO-like orbits" with "different directions of lines of apsides" which operate contemporaneously during ILWS. The RBSP spacecraft will be launched into a single petal with a common line of apsides, their separation in phase around the petal increasing over the course of the mission. When the RBSP were being planned there was an original desire for single satellites in six petals, which was later reduced to 3 petals, and eventually to two satellites orbiting in the same petal. The addition of the Canadian ORBITALS satellite mission, as well as potentially other partner ILWS missions such as the proposed Japanese ERG (Energy and Radiation in Geospace; see Shiokawa et al., 2005) could recreate this important global multiple petal coverage. Such mission co-ordination would be a great success for ILWS. Indeed, the ILWS M-TG report endorsed the ORBITALS together with the RBSP as a "scientifically recommendable solution" to this end.

4. The ORBITALS mission

Following the completion of a successful concept study, the ORBITALS mission is now entering a Canadian Space Agency funded Phase A. The ORBITALS mission will carry a complement of plasma and fields instruments necessary to reach science closure. The goal of the ORBITALS mission is to "determine the dominant processes leading to the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere".

Of significance to the ORBITALS mission goal is the realization that very important coupling exists between particles of widely differing energies. The space physics community regularly considers the importance of cross-scale coupling in space and in time, however, in relation to the radiation belts we also need to consider cross-scale coupling with respect particle populations of different energy, which become coupling through the action of waves. The ORBITALS mission will focus specifically on understanding the pathways for particle-wave-particle energy transfer which control MeV energy radiation belt particle dynamics and radiation belt morphology. For example, the cold plasma density in the inner magnetosphere influences the growth rate of EMIC waves, can control the penetration of Pc5 ULF waves into the inner magnetosphere, and influences the ELF/VLF wave propagation. In this way, radiation belt particle fluxes can be influenced by an apparently disconnected population whose energy differs by perhaps 6 orders of magnitude! The secondary science goals for the ORBITALS, in addition to their own intrinsic scientific merit, also reflect the importance of both the plasma and wave environment for meeting the primary objective of understanding radiation belt dynamics (further details about the ORBITALS science objectives can be found at www.orbitals.org). The ORBITALS science objectives are:

PRIMARY OBJECTIVE: 1) Dynamical variation of outer radiation belt electron flux, including determining the dominant acceleration and loss processes.

SECONDARY OBJECTIVES: 2) Dynamical behavior of inner zone radiation belt electron and ion fluxes; 3) Structure of global inner magnetospheric electric and magnetic fields; 4) Core ion composition of the outer plasmasphere, plasmapause and plasmatrough regions and its dynamics during storms; 5) Dynamical behavior of the strength, asymmetry, composition and energization of the ring current in the inner magnetosphere.

TERTIARY OBJECTIVE: 6) Nightside near-Earth plasmasheet flows and instabilities.

In addition, the ORBITALS will provide important monitoring of electrons and ions from the inner belt through MEO to close to geosynchronous orbit at energies (from ~ keV to ~10-100 MeV) which are important for space weather satellite charging. These measurements will be used as inputs for the development of the next generation of radiation belt specification models to replace AP-8 and AE-8. On-board space weather effects deep-dielectric charging monitors, as well as total dose and single event upset (SEU) monitors, will also measure the on-orbit effects of the space environment encountered by the ORBITALS. The new fundamental understanding resulting from these objectives will lead directly to improved space weather specification models and hence to the mitigation of space weather effects in the design of operational satellites.

4.1 ORBITALS orbit

The ORBITALS orbit is designed to meet the following criteria:

i) Low inclination orbit to measure the maximum extent of the particle distributions trapped in the mirror fields in the radiation belts.

ii) Maximize the local time and magnetic conjunctions with the extensive ground-based instrumentation in the North American sector. These include the Canadian Geospace Monitoring (CGSM; see `www.cgsm.ca`, and `www.ssdp.ca`) program including the CARISMA (formerly known as CANOPUS) and CANMOS magnetometer arrays; NORSTAR riometer, meridian scanning photometer, and all-sky-camera array; Canadian SuperDARN HF radar; and the CADI digital ionosonde array), as well as US mid-latitude magnetometer stations in arrays such as McMAC, and relevant IGPP-LANL magnetometer stations (see Fig. 3).

iii) Apogee close to GEO to provide scientific conjunctions with GOES East and West satellites, as well as space weather energetic particle monitoring of the space environment close to the fleet of commercial satellites at GEO over the Canadian-US sector.

iv) Provide coverage of the slot region between the outer and inner belts, for monitoring of slot-filling events (e.g., following the Halloween 2003 storms (Baker et al., 2004; Loto'aniu et al., 2006)).

v) Provide coverage of at least the outer parts of the inner radiation belt to probe the creation of new inner belts, and the trapping of very energetic ions.

vi) Provide particle measurements across MEO at low inclination for input into the next generation of radiation belt specification models.

vii) Within the mission lifetime provide coverage of all local time sectors to expand on the limited local time coverage obtained by CRRES.

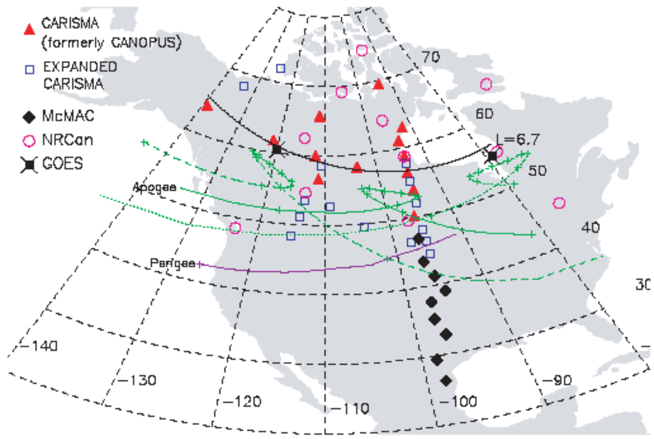

Fig. 3. Magnetic ground conjunctions for the ORBITALS with selected ground-based magnetometers in the Canadian/US sector (green traces). Tick marks are one hour apart, and the dashed traces show the ORBITALS orbit at the extrema of ~+/-20 degree longitude oscillation in ground-apogee orbits due to periodic longitudinal freely drifting orbital motion.

The baseline orbit has a 12 hour period, adopts low inclination (assumed to be nominally 7^o, consistent with that deliverable from Ariane 5 from French Guiana) and raised perigee ($r = 2.04\ R_E$ geocentric) with apogee ($r = 6.3\ R_E$) close to geosynchronous orbit in the Canadian/US local time sector. This generates daily long-lasting (~ 8 hour) apogee pass conjunctions with the extensive ground-based CGSM and other ground-based instrumentation, as well as with the GOES East and West and commercial geosynchronous satellites in the north American sector (see Fig. 3). Every second orbit will also generate a long-lasting apogee pass out toward GEO in the Asian sector East of the Indian local time sector. This generates opportunities for ground-satellite conjunctions with ground-based instrumentation in the Asian sector, as well as providing space weather monitoring for satellites operating in this sector.

The ORBITALS will be a sun-aligned spin-stabilised spacecraft, which is freely drifting with the exception of the one degree per day rotation of the spin axis required to maintain sun-alignment. A very significant strength of this orbit is the evolution of the alignment of the line of apsides through mission life. The ORBITALS orbit is a low-inclination manifestation of a Molniya orbit, except of courser that at low inclination there is drift of the apogee with respect to the ground. However, in this baseline orbital configuration the apogee alignment over the Canadian/US (and hence also the Asian) meridian oscillates periodically by approximately +/- 20 degrees longitude, the orbit precession covering 24 hours of MLT in 13.64 months. This unusual oscillation of the apogee meridian will maintain the daily magnetic conjunctions of the ORBITALS in the same ground meridian for the entire mission life (baseline mission life is 2 years).

The baseline orbits daily ground-satellite conjuctions in the Canadian/US sector will enable the ORBITALS to exploit the powerful combination of local in-situ measurements with the meso-scale monitoring of magnetic fields, waves, and particle precipitation surrounding the satellite. For example, within CGSM, CARISMA will be able to EMIC and ULF waves, as well as remote-sensing cold plasma (and plasmasphere) density profiles (e.g., Dent et al., 2006), NORSTAR will monitor precipitation across a range of energies with riometers (electrons >~ 30 keV), as well as with optical instrumentation.

Finally, daily mini-satellite constellations will be created via ORBITALS apogee passes close to the GOES satellites, ORBITALS measurements providing longer dwell times in the slot than RBSP and providing a vital link to radiation belt source populations by providing essential coverage between RBSP apogee at L ~ 5.5 and measurements at GEO by the GOES and LANL satellites.

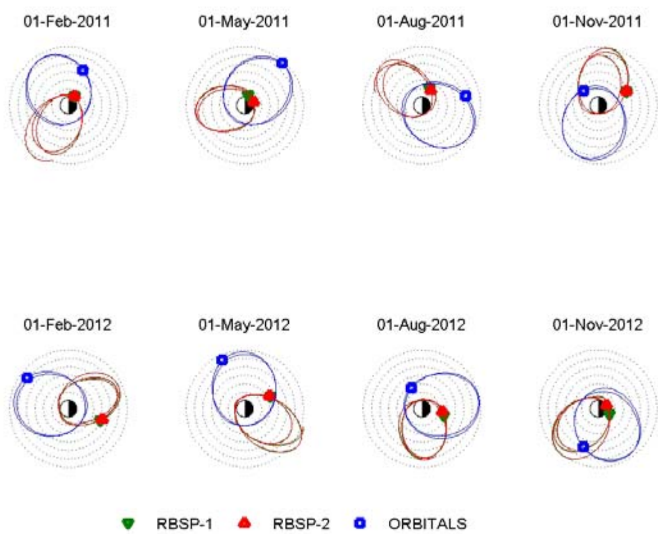

Fig. 4. Baselined local time development of the RBSP and ORBITALS petal orbits in the equatorial plane.

As discussed above, radiation belt electrons are influenced by the integrated effects of acceleration and loss processes along their drift orbits. Consequently, and as endorsed by the ILWS Magnetosphere task group, global coverage from the contemporaneous operation of the ORBITALS and RBSP would be extremely scientifically advantageous. Fig. 4 shows the baseline relative dynamics of the RBSP and the ORBITALS lines of apsides in the equatorial plane. Different rates of rotation local time enables excellent dawn and dusk coverage after launch which as the satellites chase each other develops into operation in the same local time sector towards the end of a 2-year primary mission. The latter provides improves the cadence of phase space density slices as a function of L, and provides excellent higher spatial resolution enabling spatio-temporal variations to be resolved in the satellite data. An extended mission phase would enable the dawn and dusk coverage important for resolving for example dawnside ULF and VLF acceleration at the same time as dusk-side EMIC loss to be re-visited.

4.2 ORBITALS payload

The ORBITALS science payload contains the following instrument complement, to be provided by Canadian as well as partner international instrument providers. At the time of writing, US partners within the ORBITALS team had submitted a proposal to the NASA LWS program for Mission of Opportunity funding for 4 US instruments to complete the comprehensive plasma and waves ORBITALS payload.

1) **Fluxgate magnetometer (FGM).** Boom mounted 3-component fluxgate magnetometer. DC to 50 Hz dataproduct from 180 Hz raw sampling. Canadian e-POP satellite heritage. The FGM will supply the required DC, ULF and EMIC wave monitoring B-fields required by ORBITALS science.

2) **Search coil magnetometer (SCM)**. Boom mounted tri-axial search coil magnetometer, in opposition to the FGM boom. 0.1-20 kHz with a sensitivity below 10^{-9} nT^2/Hz near 5kHz. Sampling and ADC through EFW instrument ensuring spectra and burst mode data E and B are obtained simultaneously for EMIC, VLF and other wave modes.

3) **Electric fields and waves (EFW) instrument.** Spin-plane 2D E-field from 90m tip-to-tip wire booms continuously at DC-40 Hz. 0.1 mV/m sensitivity. Baselined additional modes include boom-to-boom potential (2Hz sampling), Langmuir probe mode sweeps upto 500 kHz providing plasma and upper-hybrid line electron density measurements (5 minute cadence), and burst modes including spectra and wave-form capture (baseline burst modes: 1s at 40kHz for whistler mode, and 5s 2kHz ion scatter mode. Heritage includes ISEE-1, CRRES, Polar, as well as THEMIS and STEREO.

4) **Suprathermal ion imager (SII).** Density, flow velocity, and temperature, plus higher-order features of core ion populations in the plasmasphere and plasmatrough from 0-50 eV. 2-D distributions; 3-D once per spin. Species resolution between H+, He+ and O+, with 2D energy resolution of ~0.1 eV, and densities between 0.1-1000+ /cc. Core ion species density (important for EMIC dispersion relations) and background flows (0-20 km/s) and anisotropic distributions during plasmaspheric refilling. Heritage from GEODESIC, Cusp and JOULE sounding rockets, and e-Pop and Nozomi satellites.

5) **Energetic electron proton spectrometer (EEPS).** Two magnetic electron spectrometers (MES) with solid state telescope medium energy ion spectrometers (MIST) mounted behind. 2D (perpendicular to the spin axis) energetic ion (30

keV - 1 MeV) and electron distributions (40 keV – 2.5 MeV) once per spin. Monitors the dynamics of the energetic particles in the inner and outer radiation belt. Baseline heritage from S3-3, SCATHA and Polar/IPS.

6) **High energy proton telescope (HEPT).** Two solid state telescopes providing 2D, 3-100 MeV energetic ion coverage once per spin. Very high energy inner belt and solar proton event ion measurements. Electron channel to be investigated during Phase A. FOV canted with respect to REPT to cover pitch angles during storm-time field distortion.

7) **Composition and distribution function analyser (CODIF)**. H+, He+, He++, and O+ ions from 0.02-38 keV/q. Mass spectrometry determined 2D distributions, with 3D once per spin. Cluster flight spare from the University of New Hampshire (Reme et al., 1997).

8) **Relativistic electron-proton telescope (REPT).** Telescope measurements of ~1-10 MeV electrons, and 10-100 MeV protons. Based on SAMPEX heritage. FOV canted with repect to HEPT to better cover pitch angles during field inclination/distortion during storms.

9) **Radiation effects monitor (REM).** Two effects monitoring experiments examining i) total dose effects on MOSFET threshold voltage, and ii) single event upset occurrence by repeatedly reading out DRAM memory from processor chips. REM has heritage from STRV, and its design is described in Thomson et al., (1998).

10) **Deep-Dielectric charging monitor (DDCM).** Monitors the development of internal charge accumulation within an insulator due to MeV electron flux, providing important information about deep-dielectric charging response on-orbit. The detector is already being developed under contract from CSA Space Technology. See Balmain et al., (2003) for more details.

4.3 ORBITALS spacecraft

The ORBITALS spacecraft bus is based on the universal small satellite bus being developed for the Canadian Space Agency by Bristol Aerospace Limited (a subsidiary of Magellan Aerospace Corporation). A smaller diameter MAC-200 bus will be utilized, with mid-shelf removed, together with a revised ADCS baselined with hydrazine thrusters for spin up and sun-pointing. The mission will adopt a minimum threshold of 100 krad parts, the bus structure providing the equivalent of 4 mmAl additional shielding. A spot shielding philosophy will also be adopted for critical parts.

5. Canadian geospace monitoring (CGSM) program

The Canadian Geospace Monitoring (CGSM) program (www.cgsm.ca) is a Canadian Space Agency funded ground-based instrument program, built on the success of the previous CANOPUS program. Consisting of the CARISMA (Canadian Array for Real-time InvestigationS of Magnetic Activity; www.carisma.ca) magnetometer array, the NORSTAR riometer, all-sky camera, and meridian scanning photometer array, the Canadian SuperDARN radars, F10.7 solar radio flux monitoring, a CADI network of digital ionosondes, and a supporting Facility for Data Assimilation and Modelling (FDAM), it represents a powerful array of instrumentation in the Canadian sector.

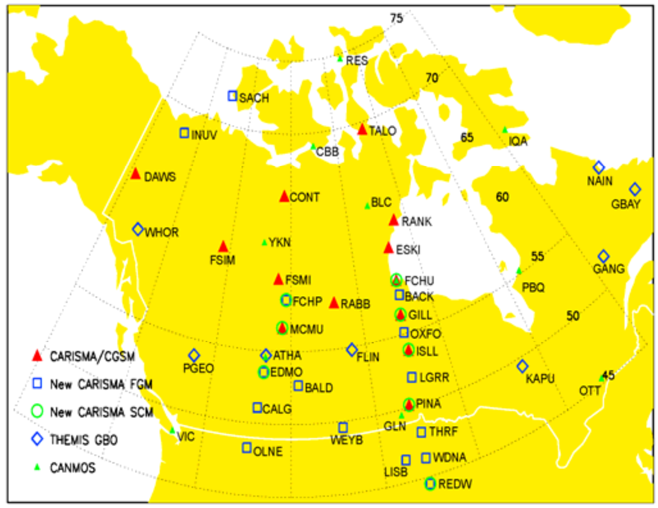

Fig. 5 CARISMA magnetometer array stations.

CGSM offers an internationally unrivalled capability to monitor the meso-scale ionospheric signatures of magnetospheric processes. Within CGSM, each of the program elements is being significantly enhanced and expanded in comparison with the previous CANOPUS program through the deployment of new instrumentation and the instigation of updated real-time satellite data collection from the field. Of particular relevance to radiation belt science and outlined here is the expansion of the former CANOPUS magnetometer array into the CARISMA array.

Upgrading from 13 stations, CARISMA will be expanded during ILWS with the addition of 15 new fluxgate magnetometers principally to increases the latitudinal density of stations along the Churchill line, extent the Churchill line to mid-latitudes within the US, constitute a new Albertan latitudinal chain, and fill in mid-latitude coverage between these two meridians. The standard fluxgate data product is has 1s cadence, upgraded from 5s; the instruments themselves monitor at 8Hz and this full high resolution data set is available on request (internal filtering cuts off the instrument response strongly above 2 Hz). In addition, a network of new 8 induction coil magnetometers will be deployed. The locations of stations in the expanded array are given in Fig. 5.

The higher resolution CARISMA fluxgate and induction coil network will allow the characterization of the ionospheric projection of currents and waves in the inner magnetosphere, specifically enabling the ground-based monitoring of ULF Pc5 and EMIC waves from the plasmasphere to the polar cap across a wide range of local times. Data is freely available from the Canadian Space Science Data Portal at www.ssdp.ca.

6. Conclusion

Since the accidental discovery of the Van Allen belts, the processes responsible for the acceleration and loss of relativistic particles in the radiation belts have remained an enigma. In-situ measurements from the equatorial plane are essential for science closure. The radiation belts are a high priority science target for the International Living with a Star (ILWS) program, and the ORBITALS satellite represents an important proposed Canadian Space Agency contribution. Carrying a suite of electric and magnetic field as well as particle instruments covering a wide range of energies, the ORBITALS will make daily long-lasting conjunctions with the extensive instrumentation in the Canadian Geospace Monitoring Program (CGSM) as well as with GOES and other commercial geostationary satellites. In combination, these conjunctions provide a powerful means to determine at meso-scales the detailed effects of proposed acceleration and loss processes and identify those which are dominant. Planned to operate contemporaneously with the approved NASA Radiation Belt Storm Probes (RBSP), the combined RBSP-ORBITALS constellation will provide the global coverage necessary for reaching science closure in understanding why the apparently astrophysically quiescent magnetosphere is such an efficient relativistic particle accelerator.

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References

D. N. Baker, “How to cope with space weather”, *Science*, vol. 297, pp. 1486-1487, 2002.

D. N. Baker et al., Disturbed space environment may have been related to pager satellite failure, *Eos*, vol. 79, p. 477, 1998.

D. N. Baker et al., “An extreme distortion of the Van Allen belts arising from the “Halloween” solar storm in 2003”, *Nature*, vol. 432, pp. 878-881, 2004.

K. G. Balmain et al., “Embedded probe floating potential charge-discharge monitor”, *Proc. 8th spacecraft charging technology conference*, 2003.

Z. C. Dent, et al., Plasmaspheric depletion, refilling and plasmapause dynamics: A co-ordinated ground-based and IMAGE satellite study, *J. Geophys. Res*., vol. 111, doi:10.1029/2005JA01104, 2006.

S. R. Elkington, M. K. Hudson and A. A. Chan, Resonant acceleration and diffusion of outer zone electrons in an asymmetric geomagnetic field, *J. Geophys. Res.*, vol. 108, doi:10.1029/2001JA009202, 2003.

R. H. W. Friedel et al., “Relativistic electron dynamics in the inner magnetosphere - A review”, *J. Atmos. Sol. Terr. Phys*., vol. 64, pp. 265-282, 2002.

J. C. Green and M. G. Kivelson, “Relativistic electrons in the outer radiation belt: Differentiating between acceleration mechanisms”, *J. Geophys. Res*., vol. 109, doi:10.1029/2003JA010153, 2004.

J. C. Green et al., “Testing loss mechanisms capable of rapidly depleting relativistic electron flux in the Earth's outer radiation belt”, *J. Geophys. Res*., vol. 109, doi:10.1029/2004JA010579, 2004.

R. B. Horne et al., “Wave Acceleration of Electrons in the Van Allen radiation belts”, *Nature*, vol. 437, p. 227, 2005.

S. G. Kanekal, D. N. Baker and J. B. Blake, “Multi-satellite measurements of relativistic electrons: Global coherence”, *J. Geophys. Res*., vol. 106, pp. 29721-29732, 2001.

T. M. Loto’aniu et al., “The relationship between relativistic electron flux enhancements in the slot region and ULF waves observed during the October 2003 “Halloween” geomagnetic storm”, *J. Geophys. Res.*, vol. 111, doi:10.1029/2005JA011355, 2006.

W. W. Liu et al., “Solar and Space Physics in the Era of International Living with a Star”, *Physics in Canada*, Jan/Feb, 2005.

W. W. Liu, G. Rostoker and D. N. Baker, “Internal acceleration of relativistic electrons by large amplitude ULF pulsations”, *J. Geophys. Res.*, vol. 104, pp. 17391-17408, 1999.

I. R. Mann et al., “The Outer Radiation Belt Injection, Transport, Acceleration and Loss Satellite”, *Adv. Space Res.*, vol. 38, pp. 1838-1860, 2006.

I. R. Mann, T. P. O'Brien and D. K. Milling, “Correlation between ULF wave power, solar wind speed and relativistic electron flux in the magnetosphere: Solar cycle dependence”, *J. Atmos. Sol. Terr. Phys*., vol. 66, pp. 187-198, 2004.

R. A. Mathie and I. R. Mann, “A correlation between extended intervals of ULF wave power and storm-time geosynchronous relativistic electron flux Enhancements”, *Geophys. Res. Lett*., vol. 27, pp. 3261-3264, 2000.

N. P. Meredith et al., “Evidence for chorus-driven electron acceleration to relativistic energies from a survey of geomagnetically disturbed periods”, *J. Geophys. Res.*, vol. 108, doi:10.1029/2002JA009764, 2003a.

T. P. O'Brien et al., “Energization of relativistic electrons in the presence of ULF power and MeV microbursts: Evidence for dual ULF and VLF acceleration”, *J. Geophys. Res*., vol. 108, doi:10.1029/2002JA009784, 2003.

T. P. O'Brien et al., “Which magnetic storms produce relativistic electrons at geosynchronous orbit?”, *J. Geophys. Res*., vol. 106, pp. 15533-15544, 2001.

T. P. O’Brien, “A framework for next-generation radiation belt models”, *Space Weather*, vol. 3, doi:10.1029/2005SW000151, 2005.

G. Paulikas and J. B. Blake, “Effects of the solar wind on magnetospheric dynamics: Energetic electrons at the synchronous orbit”, in *Quantitative Modeling of Magnetospheric Processes*, Geophys. Monogr. Ser., vol. 21, W. Olson, Ed. AGU, Washington D. C., 1979, pp. 180-201.

G. D. Reeves et al., “Acceleration and loss of relativistic electrons during geomagnetic storms”, *Geophys. Res. Lett.*, vol. 30, doi:10.1029/2002GL016513, 2003.

H. Reme et al., “The Cluster ion spectroscopy experiment”, *Space Sci. Rev*., vol. 79, pp. 303-350, 1997.

G. Rostoker, S. Skone and D. N. Baker, “On the origin of relativistic electrons in the magnetosphere associated with some geomagnetic storms”, *Geophys. Res. Lett.*, vol. 25, pp. 3701-3704, 1998.

K. Shiokawa et al., “ERG – A small satellite mission to investigate the dynamics of the inner magnetosphere”, *Adv. Space Res*., In press, 2005.

D. Summers et al., “Competition between acceleration and loss mechanisms of relativistic electrons during geomagnetic storms”, *J. Geophys. Res.*, vol. 109, doi:10.1029/2004JA010437, 2004.

D. Summers and C. Y. Ma, “Rapid accleleration of electrons in the magnetosphere by fast-mode MHD waves”, *J. Geophys. Res.*, vol. 105, pp. 15887-15896, 2000.

I. Thomson et al., “Dose-depth and SEU monitors for the STRV-1c satellite”, *IEEE Trans. Nuc. Sci*., vol. 45, pp. 2675-2770, 1998.

L. V. Tverskaya, “On the boundary of electron injection into the magnetosphere”, *Geomagn. Aeron*., vol. 26, pp. 864-865, 1986.