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THE CANADIAN ENHANCED POLAR OUTFLOW PROBE (e-POP) MISSION: CURRENT STATUS AND PLANNED OBSERVATIONS AND DATA DISTRIBUTION

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ABSTRACT

The CASSIOPE Enhanced Polar Outflow Probe (e-POP) is a Canadian small-satellite mission dedicated to the study of polar ion outflows and related magnetosphere-ionosphere coupling processes in the topside ionosphere. Scheduled for launch in 2009, it will carry eight scientific instruments, including imaging plasma and neutral particle sensors, magnetometers, dual-frequency GPS receivers, CCD cameras, a radio wave receiver and a beacon transmitter, for in-situ particle, field, and current measurements and auroral imaging and radio measurements. We present an overview of the e-POP mission, its current status and plan of observations and data distribution during the operation phase of the mission.

Keywords: Small satellite, ionosphere-magnetosphere, ion outflow, data distribution

1 INTRODUCTION

In this paper, we present an overview of the Canadian Enhanced Polar Outflow Probe (e-POP) small satellite mission, including its scientific objectives, instrument complement, measurement suite, planned observations, and data distribution. The e-POP mission will be Canada's first mission contribution to the International Living with a Star (ILWS) initiative, and it comprises three important and interconnected components: a small-satellite component to investigate atmospheric and plasma flows and related wave-particle interaction processes in the topside ionosphere, a coordinated ground-based collaboration and a theoretical assimilation component. The scientific objectives of e-POP are three-fold: to study the physics of plasma outflow from the topside polar ionosphere, in particular the micro-scale physics of the ion acceleration and wave particle interaction processes, and their auroral connections; to study the physics of radio wave propagation in the F-region and topside ionosphere, in particular the 3-dimensional structures of ionospheric irregularities, using GPS radio occultation and using ground transmitter and beacon receiver sites; and to explore the resulting escape of the neutrals, including temperature enhancement and non-thermal atmospheric escape processes.

The acceleration of polar ionospheric plasma and its subsequent outflow towards the magnetosphere is one of the most important processes in the ionosphere-thermosphere-magnetosphere (I-T-M) system (Andre and Yau, 1997). This process plays a very important role in magnetosphere-ionosphere coupling, as it provides a significant source of plasma for the inner magnetosphere and the plasma sheet (Chappell et al., 1987), and likely influences the onset of magnetic reconnection on both the dayside and the nightside (Winglee, 2004). For example, the multi-fluid MHD simulation of Winglee et al. (2005) shows that heavy ion outflow can limit (reduce) the cross-polar cap potential, act as a substantial energy sink in the auroral region, and mass load the magnetotail, thereby influencing the reconnection rate and structure and the occurrence of substorms.

A number of thermal and suprathermal ion outflow populations contribute to the overall ion outflow in the polar ionosphere (Yau and Andre, 1997), including the polar wind, auroral bulk upflow, upwelling ions, ion conics, and ion beams. A number of recent studies of ion acceleration and outflow, for example Peterson et al. (2001), Abe et al. (2004), and Strangeway et al. (2004), point to the importance of polar wind and auroral bulk upflow in the topside ionosphere as a source of cold plasma for energetic ions at higher altitudes, and underscore the scarcity of observations below 3000-km altitude relative to those at higher altitudes. In particular, the observation on FAST (Strangeway et al., 2004) revealed the important roles of the Poynting flux and precipitating soft electrons in controlling auroral ionospheric ion acceleration, and the intimate connection between ion outflow and Poynting flux in the topside ionosphere. There the Poynting flux is converted to heat through Joule dissipation and ion-neutral collisions result in the lifting of both the neutrals and the ions to the transverse heating altitudes.

A large range of latitudinal spatial scales exist in the visual aurora, from band systems 10-100 km wide that often appear as single broad arcs to auroral curtains 0.1-1 km thin that can be observed in ground-based auroral imagers. A large variety of highly dynamic small-scale structures exist within the visible aurora (Trondsen and Cogger, 1998), including auroral filaments, curls, and spirals, and features associated with extremely high speeds exceeding 10 km/s and variation time constants of 1-60 s that have apparent widths on the order of 10-100 m at the magnetic zenith. Such structures are beyond the spatial resolution of most space-borne auroral imagers, and suggest the presence of auroral acceleration processes of electron inertial length or ion gyroradius scale size. An important question is the relationship between such sub-decameter structures and those associated with auroral ion bulk upflow, heating, and acceleration in the topside ionosphere.

Atomic hydrogen and oxygen ions rapidly undergo resonant charge-exchange with their respective neutral counterparts, as well as “accidental” charge-exchange with neutral atomic hydrogen and oxygen, respectively. Thus, collisional interactions between the neutral atmosphere and the polar wind ions or suprathermal ions from other energization processes are expected to produce high-speed neutral hydrogen and oxygen atoms in the topside polar ionosphere, and possibly significant non-thermal escape of neutral atmospheric hydrogen and/or oxygen.

Likewise, charge exchange between neutral helium and polar wind He^+ ion may possibly produce a significant flux of neutral helium above the escape velocity, which might constitute a dominant mechanism for outflow of atmospheric helium and removal of terrestrial helium out-gassed from the Earth's crust. In both helium and oxygen, it is important to ascertain the presence or absence of the neutral flow components and understand the energy and momentum transfer processes between the neutral atmosphere and the ionosphere.

The polar ionosphere can refract, scatter, amplify or damp traversing electromagnetic waves, or decompose these waves through non-linearity. We plan to study wave propagation through the ionosphere between coordinated ground transmitters and the spacecraft, by measuring (or inferring) the amplitude, direction of propagation, Doppler shift and signal delay time of the incoming wave onboard the spacecraft, and to reconstruct the shapes of irregularities in the ionosphere. The state of polarization of the signal measured at both the satellite and at the ground receiver (using a full polarimeter installed at the SuperDARN radar site) will be used to infer the detailed ionospheric conditions along the propagation path, and to study the details of propagation and scattering of waves emitted by the SuperDARN radars. We will also combine the polarization measurement with the interferometric measurement at SuperDARN, to identify the propagation modes, and will measure the scattered signal received by the SuperDARN receiver from the range cell traversed by e-POP, to deduce the small-scale (~100 m) or mesoscale (~1 km) scattering ionospheric structures.

The ionosphere and atmosphere will occult a satellite of the Global Position System (GPS) constellation and act as a dispersive medium for the L1 and L2-band waves emitted by the satellite, by modifying their phase and amplitude. Thus, GPS receivers onboard an orbiting satellite such as e-POP can be used to perform ionospheric tomographic measurements, using the relative motion between the receivers and the occulted GPS satellites to produce a “tomographic” sweeping of the ionosphere. Tomographic sweeping will be achieved using a transmitter (beacon) onboard an orbiting satellite to transmit coherent electromagnetic waves at two or more frequencies and an array of ground receiving stations to receive the transmitted signals. The same principle will be investigated in the reverse sense with an array of transmitters on the ground and a single e-POP receiver. In the latter two cases, the wave frequencies are typically lower and consequently dispersion-related effects such as phase shift are larger.

2 MISSION OVERVIEW

The CASSIOPE mission is conceived as a small satellite mission with multiple mission objectives: small satellite bus development, space research, and advanced communications technology demonstration. The mission concept is to use the satellite bus developed in a generic small satellite bus program to carry the e-POP scientific instrument payload and a companion communications technology demonstration payload into an elliptical polar low-Earth orbit. In addition to its communications demonstration objective, the companion CASCADE payload is to provide the large data downlink bandwidth required for e-POP. The CASSIOPE satellite will be 3-axis stabilized, and will be placed in a polar orbit of 325 km perigee, 1500 km apogee, and an inclination of 80°.

2.1 Instrument Complement

Figure 1 depicts the layout of instruments on e-POP. The e-POP payload will consist of 8 instruments, including 4 in-situ instruments: an imaging and rapid-scanning ion mass spectrometer (IRM; PI: P.V. Amerl), which will measure ion composition and 3D velocity distributions in the 1-100 eV/e energy-per-charge and 1-60 AMU/e mass-per-charge ranges; a suprathermal electron imager (SEI; PI: D.J. Knudsen), which will measure electron energy and pitch angle distributions in the 2 – 200 eV range; a neutral mass and velocity spectrometer (NMS; PI: H. Hayakawa), which will record the mass composition and velocity or temperature of major neutral species, including atomic oxygen (O) and molecular nitrogen (N_2); and a fluxgate magnetometer (MGF; PI: D.D. Wallis), which consists of a pair of spaced fluxgate magnetometers, and will measure the geomagnetic field and infer from the measured magnetic field perturbation field-aligned current structures. The IRM and SEI instruments will measure ion and electron distributions, respectively, at a maximum temporal resolution of 10 ms, which translates into a spatial resolution of about 70 m, and the MGF will measure perturbation magnetic fields at a maximum sampling rate of 160 samples per sec, corresponding to a spatial resolution of about 40 m.

In addition to these four in-situ instruments, there will be an optical imager and 3 radio instruments: The fast auroral imager (FAI; PI: L.L. Cogger) consists of two charge-coupled-device (CCD) cameras, and will image the aurora at 630 nm and the near infrared (NIR) up to 850 nm. The NIR images will have a 100-ms exposure and a maximum pixel resolution of 400 m. The radio receiver instrument (RRI; PI: H.G. James) consists of two 6-m tip-to-tip dipoles (two orthogonal pairs of 3-m monopoles) and a digital receiver, and it will measure wave electric fields in the ELF to HF range at a sampling rate of 62,500 samples per sec using frequency down-conversion. The GPS-receiver-based attitude, position and profiling experiment (GAP; PI: R.B. Langley) is comprised of an array of 5 GPS receivers and 5 antennas, and will be used for spacecraft attitude, position, and velocity determination as well as radio occultation at a maximum data sampling rate of 20 samples per second. The coherent electromagnetic radio tomography instrument (CER; PI: P.A. Bernhardt), a tri-frequency beacon, will broadcast at three radio frequencies for total electron content measurements in conjunction with ground receiving stations.

Figure 1. Layout of e-POP instruments on CASSIOPE spacecraft; see text for full names of instruments

2.2 Planned Observations

The overall goal of e-POP is to perform in-situ particle, field, and wave measurements in the sub-decameter to few-decameter resolution range, auroral imaging in the sub-km resolution, and radio measurements in sub-km to 10-km scales. In this section, we present examples of planned observations and studies using the e-POP and other collaborative measurements.

Sub-decameter structures are frequently observed on sounding rockets in the topside auroral ionosphere, for example during the activation phase of substorms (LaBelle et al., 1986 and Burchill et al., 2004). These structures appear as highly localized packets of large-amplitude electric field waves, and often coincide with localized regions of transversely accelerated ions. These "spikelets" were typically observed for only 1 to 2 ms each. This suggests that they have a lifetime or temporal scale on the order of 1 millisecond, or a vertical or horizontal spatial scale on the order of a meter. This may explain why they have not been observed on satellites in the past, where the spatial resolution of measurements is much more limited (and typically no better than tens or hundreds of meters).

Figure 2 shows the distribution of "heating" width of lower hybrid solitary structures (LHSS) observed on the GEODESIC rocket by Burchill et al. (2004). The width of each individual LHSS was calculated from the time difference between the first and the last perpendicularly heated ion distributions and the perpendicular rocket velocity. The average width was 63 m, which is about 3 times larger than the "density depletion" width of LHSS, and the standard deviation is about 25 m. The smallest width was 13 m, which corresponds to the gyro-radius of 0.8-eV O^+ ions and the spatial resolution of the ion velocity distribution measurement. The largest width was about 190 m, which corresponds to the gyro-radius of ~180-eV O^+ ions. The fact that the "density depletion" width of LHSS is on the order of 20 m in the perpendicular direction and a factor of 3 smaller than the "heating" width is interesting. The physical explanation for this is not clear. The goal of the planned measurements on e-POP is to resolve the structures of such LHSS, at least under favorable conditions.

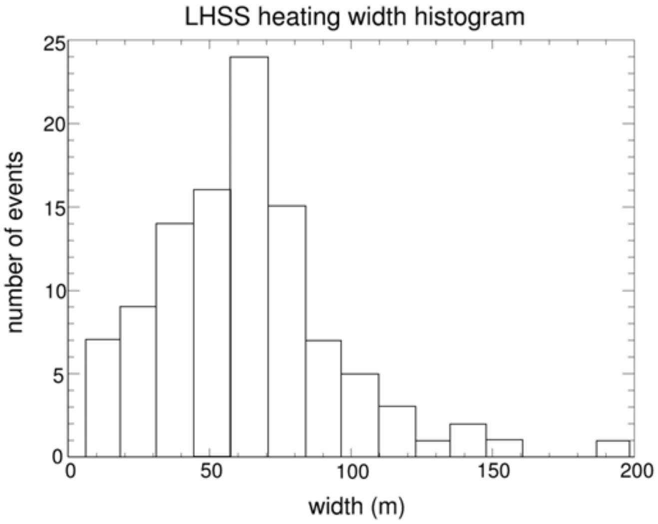

Figure 2. Distribution of observed lower hybrid solitary structure (LHSS) heating widths (from Burchill et al., 2004)

Small, km or sub-km scale structures in the aurora may presumably be linked to sub-100-meter scale structures in the plasma (density) and electric field observed in-situ. As is well known, auroral arcs are associated with several latitudinal spatial scales, ranging from 10-100 km wide auroral band systems that often appear as a single arc, to 0.1-1 km wide (thin) curtains. Of the different types of dynamic small-scale structures in the visual aurora, auroral curl is probably one of the most interesting in terms of the physics of the instabilities involved. Figure 3 is from ground-based television observations of Trondsen and Cogger (1996). The top panel in this figure shows the high-resolution snapshots of four different auroral curl systems, which were found within breakup aurora and westward traveling surges. The 1-2 km scale size of the curl is clearly evident within the field-of-view of the television camera in each case (13.5 km × 10.1 km in frame 1 and 2; 10.8 km × 10.1 km in frame 3 and 4), assuming an emission altitude of 105 km. The bottom panel in the figure shows the evolution of a curl system, at a time resolution of 0.5 s. The rotational shape and motion of the curl is anti-clockwise as viewed anti-parallel to the magnetic field.

On the 3-axis stabilized CASSIOPE/e-POP spacecraft, the FAI instrument will be operable in a number of viewing modes, including a nadir-viewing mode in which the field-of-view (FOV) of the FAI cameras will be nadir-pointing, a slew-viewing mode in which the attitude of the spacecraft will be slowly slewing and the FAI camera FOV will be set on a spatial target, and a limb-viewing mode to allow FAI to perform a limb scan of auroral emission profiles. As noted above, the FAI NIR camera (FAI-SI) will take images of 0.1-s exposure. In its routine operation mode, it will take images at 1 frame per second. Assuming an auroral emission height of 110 km, each frame ("scene") will cover a circular area of approximately 670 km diameter at e-POP apogee, and each scene element will be observed multiple times; each scene element near the center of the image will be observed at a pixel resolution of 2.6 km 120 times in a 2-min period, assuming a spacecraft velocity of 7 km/s. At perigee, the pixel resolution will be about 400 m. This will enable FAI to observe fast, small-scale auroral structures down to <1 km scales.

Previous ion composition measurements in the plasmasphere have shown that helium is usually the second most abundant ion in the plasmasphere after H^+; the observed He^+/H^+ ratio is typically about 20%. However, the concentration of heavy ions such as O^+, O^{++} and N^+ is sometimes observed to increase by a factor of 10 or more in density just inside the plasmapause when there is no corresponding variation in H^+ or He^+ ions. From DE-1 measurements, Fraser et al. (2005) showed mass loaded density profiles in which the He^+ density doubled over L = 3–4 and the O^+ density increased by over one order of magnitude, essentially eliminating the plasmapause at L = 2.5, and the resulting increase in mass loading produced a profound effect on the ULF wave field line resonance (FLR) harmonic structure. The planned ion composition observations on e-POP at plasmaspheric latitudes will be compared with ground magnetometer and ULF data to quantify the effect of mass loading on wave-particle interactions in the plasmasphere.

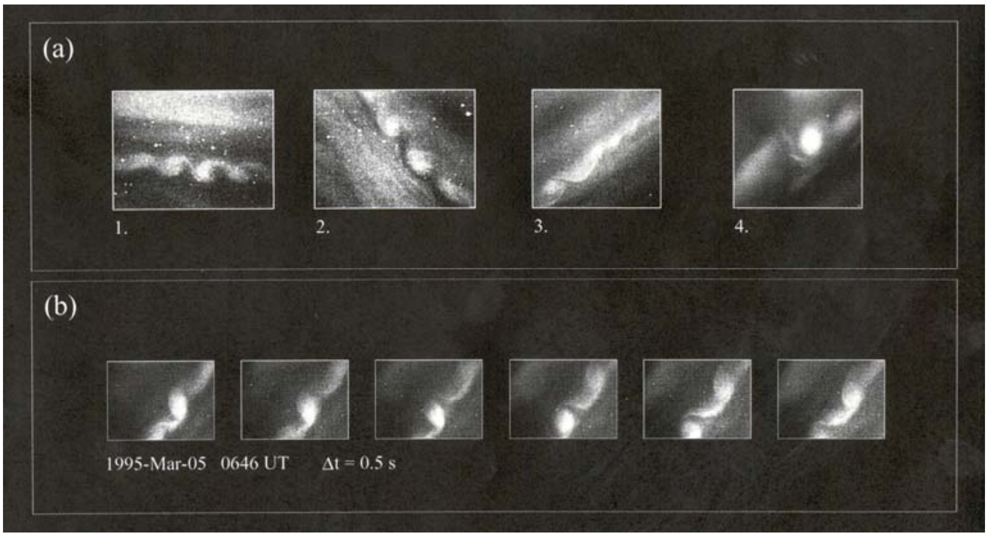

Figure 3. High-resolution snapshots of auroral curl systems observed by ground-based television cameras, from Trondsen and Cogger (1996)

As noted in the Introduction section, and in addition to the observations using the instrument payload onboard the CASSIOPE spacecraft, coordinated ground-based observations and theoretical modeling and data assimilation are the other two important components of the e-POP mission. In addition to the radio propagation experiments described earlier, we plan to conduct active experiments in coordination with a number of ground-based facilities, for example the High Frequency Active Auroral Research Program (HAARP) heating facility.

Figure 4 illustrates schematically planned coordinated observation of active ionospheric heating experiments in the HAARP heating facility in Alaska using the e-POP instruments. Such coordinated experiments will be performed during perigee e-POP orbit passes over the facility, when the e-POP spacecraft will be in the "slew" attitude mode to allow FAI to target its camera or RRI to point its antenna at the heating location. In the heating experiments, the high-power HF radio beam will be modulated at ELF and VLF frequencies, and will generate large-amplitude electromagnetic waves and ohmic heating of the ionospheric electrons in the ionosphere, which will in turn result in energetic electron flux and in a high-energy tail in the thermal electron velocity distribution. In addition, parametric decay involving Langmuir waves and ion acoustic waves will likely occur, as will the formation of cavitons by strong Langmuir turbulence. The RRI, SEI and MGF instruments onboard e-POP will seek to detect the signatures of ionospheric heating in the in-situ particle and wave data, while FAI will search for optical emissions at 630 nm associated with the heating.

2.3 Mission Data Distribution and Archival

As an integral part of e-POP science operation, e-POP mission data will be processed and reduced as soon as possible after their acquisition, and validated data will be made available as soon as possible to the e-POP Science Team and the larger scientific community via the Canadian Space Science Data Portal (CSSDP; www.cssdp.ca). Since the CSSDP is already the data portal for several other Canadian space science data sets and part of the larger virtual magnetospheric observatory, this will facilitate the simultaneous open access to both e-POP and other mission data.

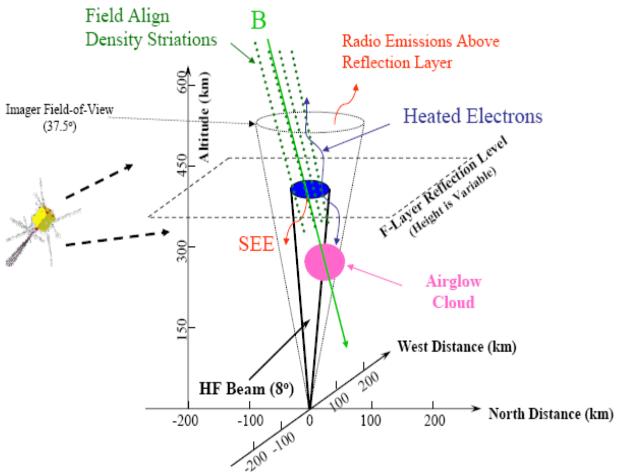

Figure 4. Schematic illustration of planned coordinated observation of HAARP heating experiments

3 CONCLUSION

The Enhanced Polar Outflow Probe (e-POP) is a part of the CASSIOPE mission, which is a multi-purpose small satellite mission sponsored by the Canadian Space Agency. The science objective of e-POP is to study plasma outflow and the associated radio wave propagation and neutral escape, as well as related ionosphere-magnetosphere coupling processes in the topside ionosphere. The mission is scheduled for launch in 2009, and is focused on the micro-scale physics of ion outflow and acceleration, and therefore on in-situ plasma and field observations at the highest possible resolution, as well as detailed studies of 3D wave propagation and fast auroral imaging. The e-POP payload has a complement of eight science instruments, including imaging plasma and neutral particle sensors, magnetometers, dual-frequency GPS receivers, CCD cameras, a radio wave receiver and a beacon transmitter, for in-situ particle, field, and current measurements and auroral imaging and radio measurements.

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