20 Years of Cluster Observations of Heavy Ion Outflow, Circulation in the Magnetosphere and Escape: Advances and Open Questions

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ABSTRACT

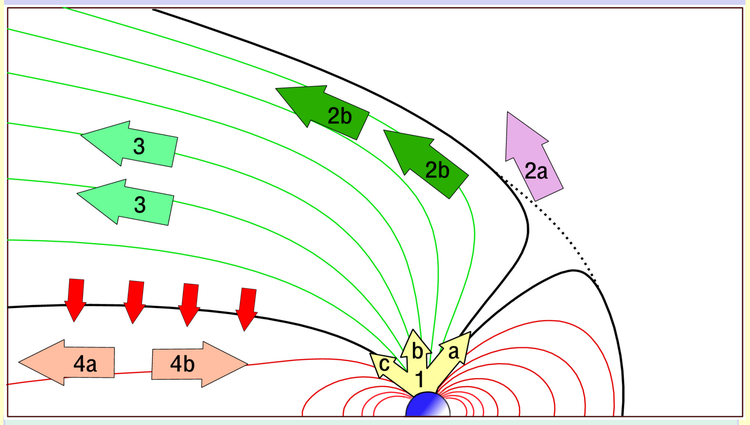
Outflow of ions from the terrestrial ionosphere and circulation in the magnetosphere plays an important role in the magnetospheric dynamics, by loading the magnetosphere with heavy atomic and molecular ions. Some of the outflowing ions can be re-injected into the inner magnetosphere, whereas some can completely escape to outer space.

Cluster was the first mission in the magnetosphere to involve four spacecraft in a tetrahedral configuration, providing 3D measurements of the space plasma parameters. The observations of the outflowing and escaping ion populations performed by Cluster are reviewed and the most prominent results highlighted.

These show the dominance in the magnetotail lobes of cold plasma outflows originating from the polar caps. For the energetic heavy ion outflow the cusps constitute the main source. The dependence of the polar outflow on the solar wind parameters and on the geomagnetic activity has been evaluated for both cold ion populations and energetic heavy ions. For the later, outflow has been observed during all periods but an increase by two orders of magnitude has been shown during extreme space weather conditions. This outflow is adequate to change the composition of the atmosphere over geological time scales. At lower latitudes, the existence of a plasmaspheric wind, providing a continuous leak from plasmasphere, has been demonstrated. The general scheme of the outflowing ions circulation in the magnetosphere or escape, and its dependence on the IMF conditions, has been outlined.

However, several questions remain open, waiting a future space mission to address them.

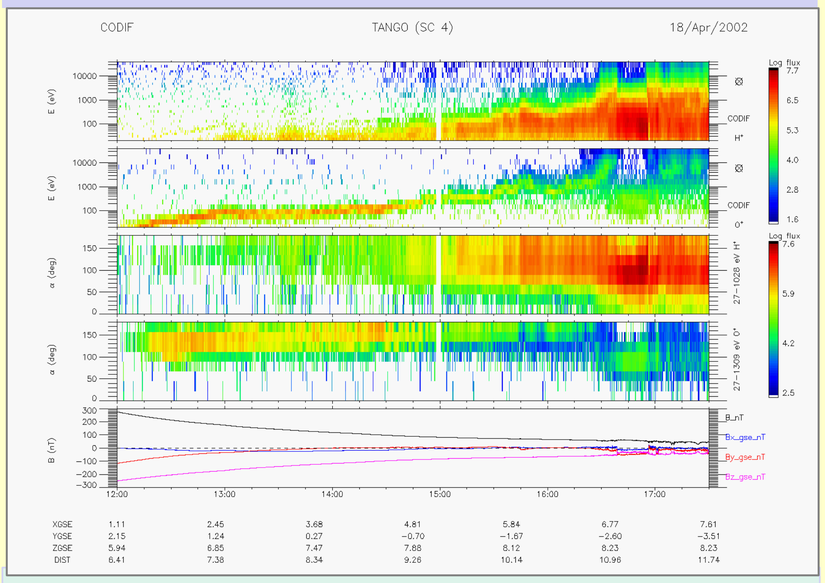
Ionospheric ions outflow paths



Green and red magnetic field lines correspond to the open and closed lines respectively. Ionospheric outflow is represented by yellow arrows. 1a – 1c, correspond to the cleft ion fountain, the polar wind and the auroral night zone outflow, respectively. Atmospheric escape to the magnetosheath is represented by direct escape from the cusp (2a) and via the plasma mantle (2b). Lower energy ions fill the lobes (3), and then feed the plasma sheet (red arrows), where both tailward and earthward transports take place.

From Slapak and Nilsson (Geophys. Res. Lett., 2018).

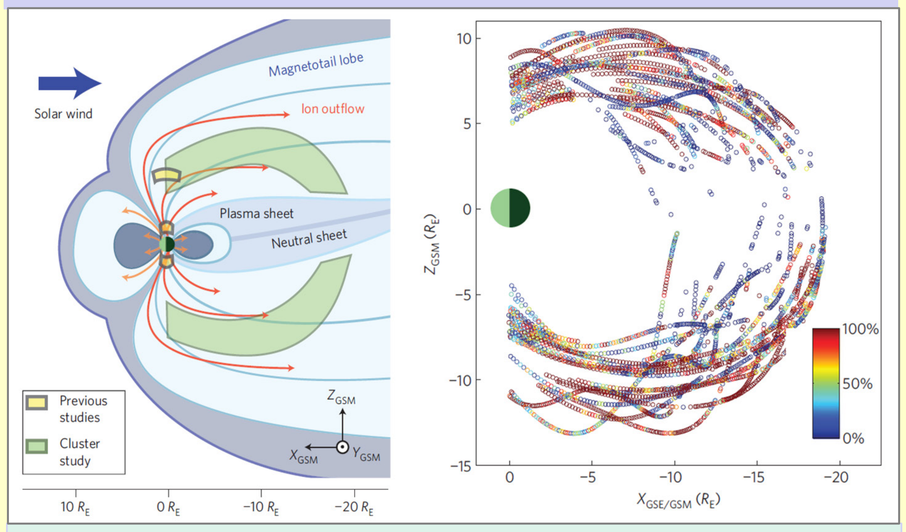
- **The cusps constitute the main source of energetic heavy ion outflow.**
- **Transport and acceleration of these ions through the polar cap into the lobes and then, depending on the IMF conditions, into the plasma sheet, has been characterised.**



Example of Cluster spacecraft C4 observation of an outflowing ion beam, detected by the CIS-CODIF instrument above the northern polar cap during an outbound orbit. The outflowing ions population corresponds to the dominant >90° pitch angle population.

Bouhram et al. (Ann. Geophys., 2004); Kistler et al. (J. Geophys. Res., 2010); Liao et al. (J. Geophys. Res., 2015); Dandouras (J. Geophys. Res., 2021)

Cold plasma outflows, originating from the polar caps, dominate the magnetotail lobes during all parts of a solar cycle, constituting a previously "hidden" population

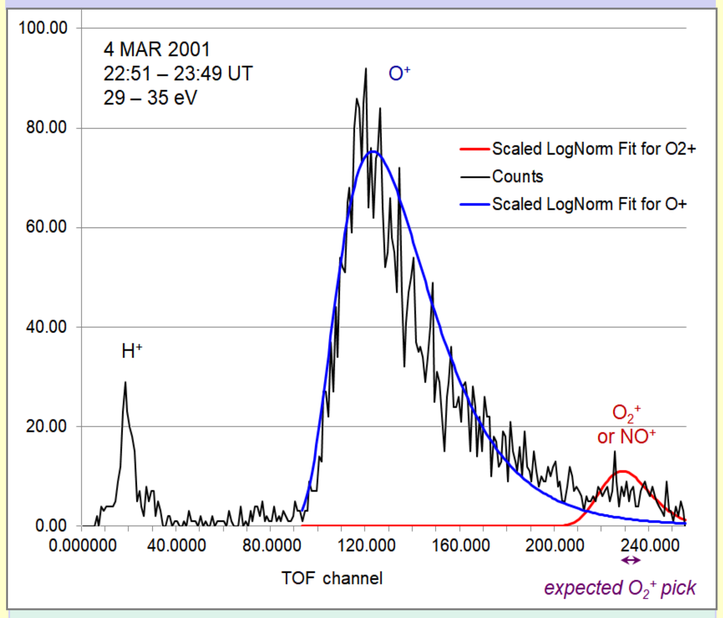


Left: Statistical studies of outflows from the polar ionosphere with energies of ~10 eV have previously been conducted close to the Earth by Akebono and Polar. The Engwall et al. (2009) study with Cluster covered a much larger volume in regions where these ions had been previously invisible.

Right: Parts of Cluster orbits for which the wake method to detect cold ions was used. Each point in the graph corresponds to 10 min of data and the colour shows the relative occurrence of cold ions.

From Engwall et al. (Nature Geosci., 2009).

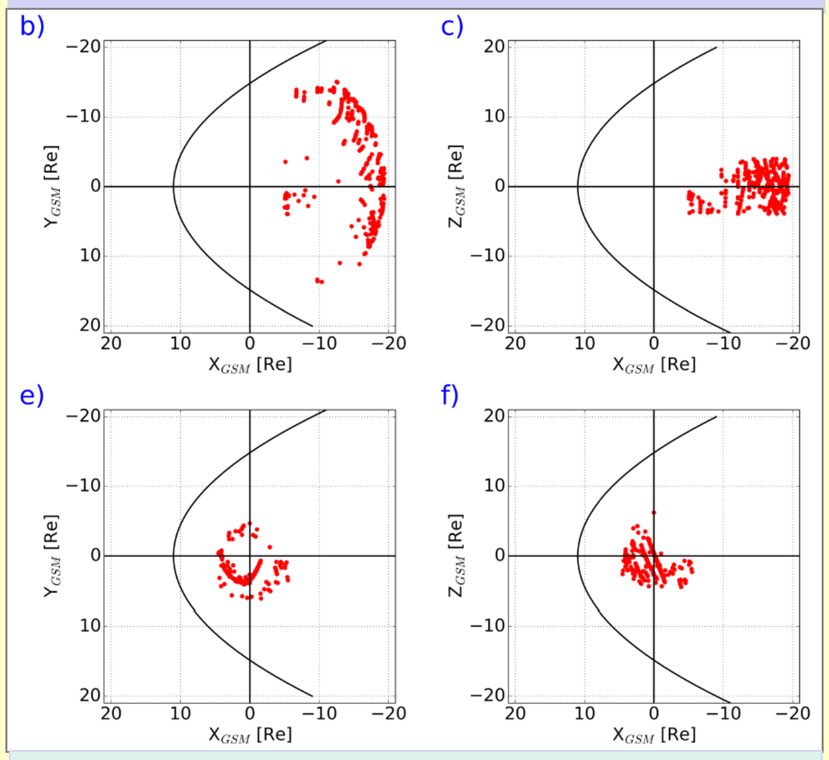
Heavy molecular ions observed outflowing during high-activity conditions



Time-of-flight spectrum for the low-energy ions detected by CIS onboard Cluster-C1 during the 4 March 2001 event, where two interplanetary shocks struck the magnetosphere, followed by a strongly southward oriented IMF . The spacecraft was over the southern polar cap at R = 7 R_E. Observation of an upwelling ion population containing H^+, O^+ and O_2^+ or NO^+ ions.

From Dandouras (EPSC, 2017).

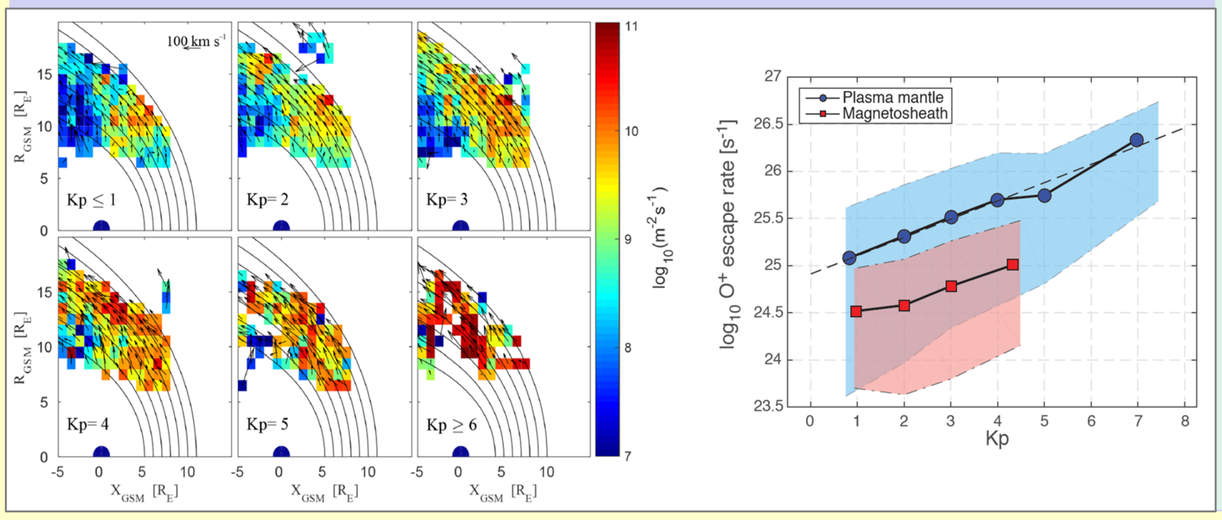
- **Suprathermal Fe ions can be found all over Geospace.**
- **The time variation is consistent with a modulation by geomagnetic disturbances and the solar activity.**



Suprathermal Fe detection by RAPID onboard Cluster in the nightside plasma sheet and in the inner magnetosphere.

From Haaland et al., (J. Geophys. Res., 2020).

- **The dependence of the polar outflow on the geomagnetic activity level has been evaluated and a logarithmic law established.**
- **During extreme activity conditions the heavy ion loss is almost two orders of magnitude higher than during typical average conditions.**
- **The heavy ion loss measured by Cluster, when integrated over the past four billion years and considering the much more active young Sun, suggests a total O^+ loss comparable to the amount of oxygen contained today in the terrestrial atmosphere.**



Left: The spatial distribution of the plasma mantle O^+ bulk flow flux, for periods of different geomagnetic conditions. The colour bar defines the average flux intensity, and the arrows the O^+ bulk velocity.

Right: Average O^+ escape rates for the plasma mantle (blue circles) and the dayside magnetosheath (red squares) as a function of Kp. The dashed black line is a least squares fit to the logarithm of the average escape rates for the plasma mantle. The thin dot-dashed lines correspond to estimated upper and lower O^+ escape rates in the plasma mantle (blue area) and the magnetosheath (red).

From Slapak et al. (Annal. Geophys., 2017).

The general scheme of the circulation of outflowing ions in the magnetosphere or escape, and its dependence on the IMF conditions, has been outlined for both cold ions and for heavy energetic ions

Schematic representation of the circulation of outflowing ions in the magnetosphere and their destination.

From Yamauchi (Annal. Geophys., 2019).

Heavy Ion Outflow, Circulation in the Magnetosphere and Escape: Other Major Cluster Advances

- The role of the centrifugal acceleration in the energisation of the ions upflowing from the polar caps has been demonstrated (*Nilsson et al., Ann. Geophys., 2008*).
- The dependence of the polar outflow on the solar wind parameters has been evaluated for both cold ion populations and heavy energetic ions *(André et al., J. Geophys. Res., 2015; Li et al., J. Geophys. Res., 2017; Schillings et al., Earth Planets and Space, 2019*).
- The outflow of moderate energy light and heavy ions, forming beams that originate from the auroral oval, has been established even for periods without substorms (*Maggiolo et al., Ann. Geophys., 2011; Parks et al., Ann. Geophys., 2015*).
- At lower latitudes, the existence of a plasmaspheric wind has been demonstrated (*Dandouras, Ann. Geophys., 2013*).
- Cluster light and heavy ion outflow observations cover almost two solar cycles, providing a data base for comparative studies with other planetary atmospheres.

Open Questions

- The **exact degree of plasma recirculation for each ion species**, after it has left the ionosphere, **versus direct or indirect escape, and its dependence on the solar and geomagnetic activity conditions**, needs to be assessed more precisely.
- The **exact composition** of the escaping populations, and how it changes in response to the different driving conditions, is an open question: How does the composition of the escaping populations change in response to different driver conditions, and in particular **how does the nitrogen / oxygen escape ratio change?**