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Detection of cold gas releases in space via low energy neutral atom imaging

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ABSTRACT

Low energy neutral atoms (LENAs) are produced in space plasmas by charge exchange between the ambient magnetospheric plasma ions and cold neutral atoms. Under normal conditions these cold neutrals come from the terrestrial geocorona, a shroud of few-eV hydrogen atoms surrounding the Earth. As a consequence of this charge exchange, it has become possible to remotely image many regions of the magnetosphere for the first time utilizing recently developed LENA imaging technology. In addition to the natural hydrogen geocorona, conventional explosions and maneuvering thruster firings can also introduce large amounts of cold gas into the space environment. In this paper we examine whether such potentially clandestine activities could also be remotely observed for the first time via LENA imaging. First, we examine the fluxes of LENAs produced in the space environment from a conventional explosion. Then we review the present state of the art in the emerging field of LENA detection and imaging. Recent work has shown that LENAs can be imaged by first converting the neutrals to ions with ultra-thin (10s of Å) foils and then electrostatically analyzing these newly created ions to reject the large ($>10^{10} \text{ cm}^{-2} \text{ s}^{-1}$) UV background to which the low energy detectors are sensitive. We conclude that the sensitivities for present LENA imager designs may be just adequate for detecting some man-made releases. With additional improvements in LENA detection capabilities, this technique could become an important new method for monitoring for conventional explosions, as well as other man made neutral releases, in the space environment.

1. INTRODUCTION

The terrestrial magnetosphere is a complicated and highly dynamic region which is filled, to greater and lesser extents, with plasma ions (less than a few 10s of keV) and energetic ions (greater than a few 10s of keV). This same region also contains a stable population of low energy (sub- to few eV) neutral hydrogen atoms called the geocorona¹. When the plasma ions and energetic ions undergo charge exchange with the geocoronal neutrals, low energy neutral atoms (LENAs) and energetic neutral atoms (ENAs), respectively, are created. Since these newly formed neutrals are unaffected by electric and magnetic fields, ENAs and LENAs radiate through the magnetosphere with the velocities they had at the instant of charge exchange. Remote imaging of these neutrals provides line of sight integrated observations of the convolution of geocoronal neutrals with distributions of magnetospheric energetic particles^{2,4} and plasmas^{5,7}.

To date, magnetospheric imaging with charge exchange neutrals has been discussed as a critical new technique for examining the global morphology and dynamics of the terrestrial magnetosphere and other space plasmas¹⁻⁷. However, since the LENA signal observed remotely is actually due to both the ion and low energy neutral populations at the source, such observations might also reveal variations in the cold

neutral background. We are unaware of any natural phenomena that would substantially enhance the density of low energy neutrals in the magnetosphere. There are, however, a number of man-made phenomena, such as the detonation of conventional high explosives and the firing of maneuvering thrusters, that could introduce substantial new cold neutral material into the space environment.

Higher energy ions (the source of ENAs) are abundant in the inner portions of the terrestrial ring current. However, lower energy ions (the source of LENAs) are dominant throughout the remainder of the magnetosphere. Some regions, such as the outer portions of the ring current, the dayside extension of the plasma sheet, the plasma sheet proper, and the magnetosheath are populated only by lower energy plasma ions. In addition, charge exchange between magnetospheric ions and the cold neutrals has larger cross sections at lower energies (see Moore et al.⁷, and references therein). Consequently, most of the magnetosphere radiates higher fluxes of LENAs than ENAs and LENA imaging provides for remote observation of a larger portion of the magnetosphere than ENA imaging⁵⁻⁷.

In this paper we first examine potential man-made sources of cold gas in the terrestrial magnetosphere (Section 2). In Section 3 we present the general technique presently best developed for imaging LENAs. In this section we also examine the sensitivities presently achievable with such observations. In Section 4 we briefly review this work and discuss possible avenues for improving LENA imaging capabilities for observing man-made releases.

2. MAN-MADE SOURCES OF COLD GAS IN SPACE

The remote detection of releases of cold, gaseous material in space represents a very significant technical challenge. However, the potential applications of such measurements are extremely far-reaching. Cold propulsion gases are released when space vehicles maneuver, thus revealing their changes in position in near-real time. Moreover, detection of an expanding neutral cloud (at one to several km/s) would provide an unambiguous indication of a conventional explosion in space. Such explosions are extremely difficult to detect, locate, and diagnose because their only primary signal, an optical flash, is very short lived and can be extremely low intensity. Since cold gas emissions cannot be contained or hidden, detection of such releases would provide a nearly irrefutable signature of such an explosion. In addition, since typical residence times of neutral atoms in the space environment are quite long (tens of minutes to hours), detection with a sufficiently high sensitivity would not rely on a single transient signature. Rather, confidence in the event would be built up over long intervals of observation.

The total number of cold gas molecules introduced into the magnetospheric environment, N_{tot} , can be readily determined from the total mass, M , of the released material and Avogadro's Number, N_A ,

$$N_{\text{tot}} = M N_A / m \quad (1)$$

where m is the average molecular weight of the released material. A conventional explosion yields molecular byproducts typically consisting of H_2O , CO_2 , N_2 , CO , C , etc. If, for example, a 100 kJ explosion yielded molecular byproducts with an average molecular weight of 30 amu, 3×10^{27} molecules of cold gas would be released.

Background coronal densities have been determined from ultraviolet photometer observations from

several spacecraft. These observations generally agree fairly well and the most recent and complete analysis (from the Dynamics Explorer 1 spacecraft) yields results consistent with a Chamberlain model exosphere with an exobase temperature of 1050 K and an exobase density of $4.4 \times 10^4 \text{ cm}^{-3}$ at 500 km altitude¹. This fit gives, for example, geocoronal densities of 500, 100, and 45 cm^{-3} at geocentric distances of $3 R_E$, $5 R_E$, and $6.7 R_E$ (geosynchronous orbit), respectively.

Neutral densities created by the introduction of new material depend on the volume of space over which the gas is distributed. Figure 1 shows the ratio of the neutral number density of released gas to the natural geocoronal density at geosynchronous orbit, as a function of the diameter of the release. For this simple calculation we assume the released material is evenly distributed throughout a spherical volume. The three dashed lines show releases of 10, 100, and 1000 kg of new material with an average molecular weight of 20. The horizontal line at a density ratio of one indicates when the release density has dropped to that of the natural background; this occurs at cloud diameters of ~2200, 5000, and 12,000 km, for the three release masses, respectively. For a conventional explosion, speeds of several km/s are typical; debris clouds from such explosions should take from several to tens of minutes to expand to such diameters.

Figure 1. Ratio of the density of the neutral cloud of released material to the background neutral density of hydrogen at geosynchronous orbit. The dashed lines represent releases of 10, 100, and 1000 kg of cold gas with an average molecular weight of 20 amu. The horizontal line indicates the point at which the density of the released gas is equal to that of the geocorona.

For a real conventional explosion, the density distribution within the release depends on the velocities of the gas molecules. Initially, the release density is very high and the cloud is collisional; as the cloud expands, the density drops and the release gas becomes non-collisional. Since there is nothing in the natural space environment to impede the outward motion of the gas once it is non-collisional, molecules simply continue to move outward with their instantaneous velocities. Owing to this expansion, the center of the release region will become depleted, and the cloud will become hollow in the middle. Therefore, the densities at the edges of such expanding clouds will be somewhat greater than shown in Figure 1 for any given cloud size.

In contrast to conventional explosives, cold gas maneuvering thrusters generally release only small quantities (<1 g to >1 kg) of neutral gas, depending on the specifics of the maneuver. On the other hand, such thrusters expand gas in only one direction. Consequently, the local densities can again remain substantially greater than the natural geocoronal densities for many minutes.

Figure 2 displays the results of a simulation of a neutral release at geosynchronous orbit in a Mercator projection. The Earth's magnetic field is approximated as a dipole in the center of each panel. The spacecraft spin axis is parallel to the dipole axis and the spacecraft is located at the magnetic equator. The vertical axis is the elevation angle between the look direction and the spin axis; the horizontal axis is the azimuthal look direction sampled as the spacecraft spins. The grayscale value for each $4^0 \times 4^0$ pixel is the logarithm of the unidirectional LENA flux for the raypath centered in that pixel. The LENA flux, $J_{\text{LENA}}(E)$, is given by

$$J_{\text{LENA}}(E) = \sum_i \sigma_i \int_l J(\mathbf{r}, E, \alpha) n_i(\mathbf{r}) dl \quad (2)$$

where σ_i is the charge exchange cross section for the interaction $H^+ + X_i \rightarrow H + X_i^+$; X_i represents the i -th neutral byproduct of the explosion. The flux $J(\mathbf{r}, E, \alpha)$ of magnetospheric protons is in general a function of location, $\mathbf{r}$, in the magnetosphere, proton energy, E (5 keV in this figure), and pitch angle, α , relative to the local magnetic field. The neutral gas number density, $n_i(\mathbf{r})$, also depends on position. The integral is performed over the entire line-of-sight path, l . This integral presupposes the medium is optically thin; i.e., the probability of a newly formed LENA undergoing a second charge exchange reaction before detection is negligible. This assumption is reasonable once the cloud has expanded, however, reionization may be an issue for LENAs transiting the central region of the cloud at early times after the release. In addition, we do not include electron-ion recombination or photoionization of neutralized magnetospheric ions due to their extremely small cross sections.

For the plasma flux, we consider only the ring current although, depending on the magnetospheric region, other plasma populations may exist. The ring current is the bright central region in Figure 2. We use a statistically average empirical shape for the magnetopause (the separatrix between magnetospheric and solar wind plasmas) which is cylindrically symmetric about the Sun-Earth line. The model nightside ring current boundary is defined by reflecting the dayside magnetopause about the terminator. We assume a simple model of the quiet time ring current plasma flux is given by

$$J_{\text{quiet}} = \begin{cases} 1.0 \times 10^5 \exp[0.46 - (R - 3.5)] [\text{cm}^2 / \text{s keV}]^{-1} & R < 3.5 R_E \\ 1.0 \times 10^5 \exp[3.00 - 3.5(R - 3.5)] [\text{cm}^2 / \text{s keV}]^{-1} & R > 3.5 R_E \end{cases} \quad (3)$$

This model gives fluxes at geosynchronous orbit of $\sim 2 \times 10^4$, consistent with typical fluxes frequently observed over the energy range of > 40 keV with the MPA instruments in geosynchronous orbit⁸. Details

Figure 2. The logarithm of the LENA flux plotted in a Mercator projection. The Earth is in the center of each panel, the explosive release, observed as the enhanced region to the left of the Earth, is based on a 100 kt conventional explosion observed from a distance of 1000 km, both the release and the observer are assumed to be in geosynchronous orbit. The three panels represent release radii of 120, 600, and 1200 km.

of the model and simulation technique used are given by Moore et al.⁷.

The LENA flux from the release is observed to the left of the Earth in each of the panels in Figure 2. The neutral release is assumed to arise from a 100 kg conventional explosion yielding 25 kg of H₂O, 25 kg of CO₂, 25 kg of N₂, and 5 kg of CO; the other 20 kg of material is assumed to be tied up in larger byproducts (including soot) that do not participate substantially in the charge exchange process. As for Figure 1 we use the simplistic assumption that the release is a spherically expanding cloud of uniform density. For an expansion velocity of 2 km/s, the images shown would represent times of 1, 5, and 10 minutes after detonation.

Because the release cloud (and, in fact, magnetosphere as a whole) is an extended source, comparable fluxes would be observed from almost any distance. As the observer moves away from the emitting region, the flux from each parcel in that region drops off with the distance squared. On the other hand, for an instrument with a fixed angular acceptance, the volume of the emitting region observed increases with the square of distance from the emitting region so that the overall flux remains constant as long as the emitting region is larger than the viewing pixels. In other words, fluxes observed for at least the two lower panels in Figure 2 would be the same if viewed from say five times further away (10,000 km), although the release would be observed across a smaller number of pixels. This argument suggests that LENA imaging may be nearly equally useful over a fairly large range of observing distances.

3. LENA IMAGER DESIGN AND CAPABILITIES

LENAs are difficult to observe in space owing to the large Ly- α ultra-violet (UV) background: low energy detectors capable of directly detecting LENAs, such as channel electron multipliers (CEMs) and microchannel plates (MCPs), are also sensitive to UV photons. Typical direct solar and scattered geocoronal Ly- α fluxes are $\sim 3 \times 10^{11}$ and $\sim 2 \times 10^{10}$ cm⁻² s⁻¹, respectively⁹. Since the Ly- α background is many decades larger than the LENA signal, this background must first be rejected in order to image the low LENA fluxes in the magnetosphere. Any such rejection technique needs to be extremely efficient ($\sim 10^{10}:1$) while still providing a large throughput for the LENAs.

The only technique well developed for imaging LENAs at this time^{5,6} relies on modifying the LENA charge state and subsequently deflecting them away from the path of the large UV background. The charge state modification (ionization) in this technique occurs as the incident neutrals transit an ultra thin foil (~ 0.5 μ g/cm²)^{5,6,10}.

3.1 Basic LENA Imager Design

Figure 3 schematically shows the four basic components of a foil conversion based LENA imager; these components are summarized in turn below. Further details about this technique can be found in M. Comas et al.^{5,6}. While a full LENA imager of the type described here has never been flown, a simpler (non imaging), thicker foil implementation of this technique was flown on a sounding rocket in 1970¹¹. Regrettably, the limited observations from this brief experiment were never unambiguously interpreted. Nonetheless, all four of the LENA imager components described here have very substantial flight histories; there can be little doubt that the manufacture and instrumentation of this type is mature and fully flight ready.

Figure 3. Schematic diagram of the essential elements of a LENA imager: 1) a collimator with high voltage on alternate plates to sweep out charged particles, 2) an ultra-thin foil for ionizing some fraction of the incident neutrals, 3) an electrostatic analyzer, and 4) a coincidence detector. Taken from McComas et al.⁶.

1. The entrance to the instrument is through a collimator section which has high voltages applied to alternate collimator plates. The collimator serves two purposes: setting the entrance angular resolution in spin phase and removing the ambient charged particles. The first effect is achieved simply through the geometric configuration of the collimator plates while the latter is accomplished by the large electric fields between the plates which sweep out entering ions and electrons with energies in the range of interest for LENA observations.

2. Immediately following the collimator is an ultra thin ($\sim 0.5 \mu\text{g}/\text{cm}^2$) foil¹⁰ which serves to ionize a substantial fraction of the entering LENAs. LENAs are traveling so slowly, and undergo so many charge exchange interactions while in the foil, that they come into charge state equilibrium during their transit¹⁰. Consequently, the exit charge state distribution is independent of the entrance charge state and rather depends simply upon the material properties of the foil and the LENA species and energy. Figure 4 summarizes the positive ion conversion efficiencies for the dominant magnetospheric LENA species, hydrogen and oxygen, as a function of incident energy for a thin carbon foil¹⁰. The ionization efficiency is sufficiently large (particularly for hydrogen) that a substantial fraction of all LENAs entering the instrument through the collimator are converted to ions and subsequently detected over the LENA energy range (1-40 keV).

Figure 4. Measured fraction, f , of atomic H and O that exit a 0.5 mg/cm^2 carbon foil as singly charged positive ions as a function of incident energy.

3. Newly formed ions from the foil are post-accelerated into a curved plate electrostatic analyzer. Ions within a certain energy/charge passband (depending on the voltage applied across the plates and the mechanical configuration of the analyzer) pass through the analyzer, while electrons, ions outside the passband, and photons hit one or the other of the analyzer plates and are rejected. Electrostatic analyzers have made *in situ* observations of the local space plasma environment on numerous space missions since the early 1960s, and their utility for making energy/charge measurements of ions while excluding the tremendous solar UV background in space has been proven many times over.

4. Ions within the E/q passband transit the analyzer and enter the detector section of the instrument. Depending on the bending angle of the analyzer, some combination of exit location and trajectory determines each ion's path through the electrostatic analyzer, and hence, its angle of incidence into the LEENA instrument. While such observations could, in principle, be made with a simple CFM or MCP detectors, the addition of time-of-flight coincidence detection greatly enhances the signal-to-noise ratio by rejecting the backgrounds caused by directly penetrating radiation and detector dark counts.

3.2 LENA Imager Sensitivity and Count Rates

The sensitivities, geometric factors, and duty cycles of LENA imagers have been examined in detail by McComas et al.⁶. For the purposes of this study we recount that the count rate, C , observed in a viewing pixel for a given flux of LENAs, J_{LENA} , is

$$C = G J_{\text{LENA}} E \quad (4)$$

where E is the energy of the LENAs and G , the per pixel geometric factor of the instrument, is a measure of the instrument's sensitivity and efficiency (after Gosling et al.¹²). The count rate per viewing pixel calculated from (4) assumes that J_{LENA} is constant over the particular energy passband and angular pixel.

The angular resolution required for observing releases is a function of the viewing distance. For the example shown in Figure 2, the release is $\sim 40^\circ$ and $\sim 80^\circ$ across in the middle and bottom panels, respectively; the resolution of our simulation ($4^\circ \times 4^\circ$) is clearly much finer than required for observing this release. A coarser resolution of $\sim 10^\circ \times 10^\circ$ would be sufficient for this release at ~ 2000 km distance. The angular resolution of the LENA imager is an important consideration because it enters into the per pixel geometric factor of the instrument⁶.

A full instrument geometric factor of $\sim 1 \text{ cm}^2 \text{ sr eV/eV}$ is an appropriate goal for a high sensitivity LENA imager of the type described in Section 3. In order to achieve such a large geometric factor, each of the instrument components needs to be optimized⁶. For $10^\circ \times 10^\circ$ resolution, an achievable per pixel geometric factor would be $\sim 0.02 \text{ cm}^2 \text{ sr eV/eV}$. Using equation 4, the per pixel count rate for the release flux shown in the middle panel of Figure 2 is $\sim 2 \text{ s}^{-1}$. For a staring instrument fixed on a single energy passband, this flux should be sufficient for a reasonable measurement since ~ 400 counts (5% statistics) would be collected per pixel over a roughly 200 s (three and a third minutes) integration.

A spinning spacecraft has obvious advantages for LENA imaging because observations can be made over all or nearly all possible look directions simply by sweeping a single fan-shaped field-of-view (FOV). This technique is already the standard for making *in situ* plasma measurement over large fields-of-view and was assumed in the production of the images in Figure 2. The drawback of these sorts of observations is that an instrument on a spinning spacecraft has a small duty cycle for observing any given look direction. For 10° angular resolution in spin angle, the duty cycle for observing a given direction is only ~ 0.05 ; on such a spinning platform the same 200 s integration discussed above would yield only ~ 20 counts/pixel. An image based on such statistics might provide an indicator of a neutral release, but would probably be at the limit of what can be reasonably interpreted.

4. DISCUSSION

This paper has provided the first analysis of the capability for observing releases of cold neutral gas in space using the recently developed techniques of low energy neutral atom imaging. We showed a specific example of a 100 kg conventional explosion at geosynchronous orbit as viewed from 2000 km away, also at geosynchronous orbit (Figure 2). The LENA fluxes produced depend not just on the amount of neutral material released, but also on the local ion fluxes. These ion distributions are highly dependent on both the specific location in and geomagnetic activity level of the magnetosphere.

Ring current ions (with energies of several keV to tens of keV) commonly fill the region from $\sim 3-8 R_E$, except at high latitudes. Monitoring of cold gas releases throughout this entire region of the magnetosphere may be feasible given a neutral atom imager with the appropriate energy range and sensitivity. In order to separate neutral releases from changes in the natural magnetospheric environment, LENA imaging would need to be routinely carried out and an understanding of the effect of natural magnetospheric variations on LENA images would need to be achieved.

The LENA imager outlined above represents the only presently well developed sensor for imaging LENAs in space. There are, however, several possible improvements and alternate imaging techniques which could provide enhanced sensitivity and, consequently, an improved ability to observe both the natural magnetospheric plasmas and man-made releases of cold neutral material. Clearly, from the preceding discussion, a pointing detector on a non-spinning platform would provide higher sensitivity simply by removing the duty cycle of scanning other look directions. In the above example this amounted to a factor of about 20 in integration time. While an excellent approach to viewing a limited region of space, such directed observations would not be appropriate for monitoring very large regions or the whole sky.

Geometric factors given above were based on the assumption that the LENA imager was limited to the resources typically available for scientific space plasma instrument (mass ~ 5 kg and volume $\sim 0.1 \text{ m}^3$)⁶. Clearly a LENA imager's sensitivity scales up with the size of the instrument since its aperture area is one of the main terms in the instrument's geometric factor. A substantially larger imager could provide appreciably greater sensitivity.

In developing a LENA instrument for scientific observations of the natural magnetospheric environment, it is important to make differential observations (several energy passbands) covering the entire range of plasma energies ($\sim 1-40$ keV). Such observations allow the various plasma populations to be independently characterized, but also require an additional duty cycling between the various passbands. For an instrument designed to look for man-made neutral gas releases, on the other hand, an integral measurement, covering the largest possible range of energies, is more appropriate. This latter design criteria enhances the observing capability of a LENA imager in two ways: 1) the integral flux is much larger than the differential flux in a small energy passband, and 2) since there is only a single energy band, there is no duty cycle reduction for the observations in each of passbands. Note that the calculation given in the previous section already assumed that the LENA sensor stays fixed on a single energy passband precisely to avoid this latter problem. A neutral imager which provided integral measurements from ~ 1 keV to several tens of keV could achieve a geometric factor 5-10 times larger than that given above. Several approaches to developing this sort of LENA imager are under active investigation at Los Alamos at this time.

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