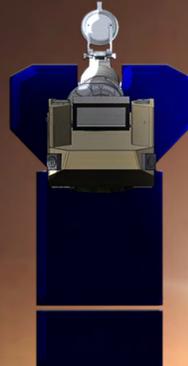
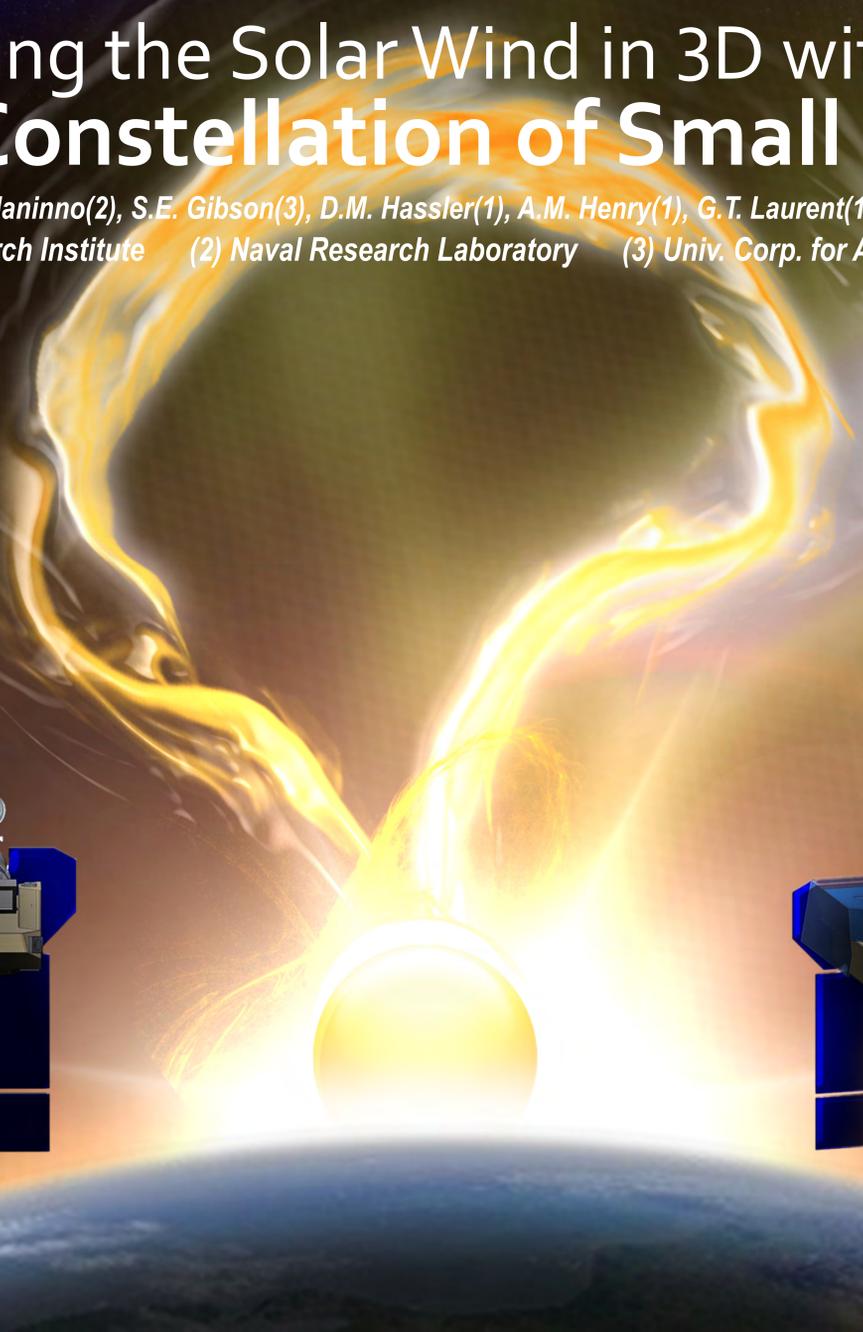


# Imaging the Solar Wind in 3D with the PUNCH Constellation of Small Satellites

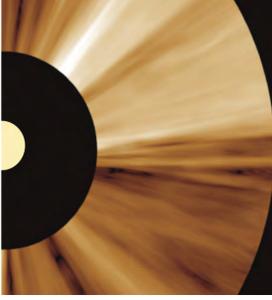
C.E. DeForest(1), A. Caspi(1), R.C. Colaninno(2), S.E. Gibson(3), D.M. Hassler(1), A.M. Henry(1), G.T. Laurent(1), R. Killough(1), and the PUNCH Team  
 (1) Southwest Research Institute (2) Naval Research Laboratory (3) Univ. Corp. for Atmospheric Research



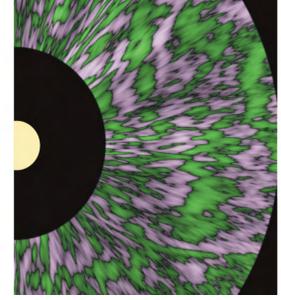
**ABSTRACT:** The Polarimeter to UNify the Corona and Heliosphere (PUNCH) is the latest Small Explorer mission being developed for NASA. Beginning in 2023, PUNCH will use polarized visible-light imaging to understand how the Sun's corona becomes the solar wind that fills our solar system. The space segment of the mission is a constellation of four small satellites (~50kg each) that work together to form a "virtual instrument" with a 90°-wide field of view centered on the Sun. The physical instruments comprise a coronagraph ("Narrow Field Imager", NFI) and three heliospheric imagers ("Wide Field Imager", WFI) that together sweep out the entire field of view. The instruments are sensitive to polarization, to enable imaging bright features in 3D using the physics of Thomson scattering. PUNCH is being built by a partnership of Southwest Research Institute, the U.S. Naval Research Laboratory, and the Rutherford Appleton Laboratory.



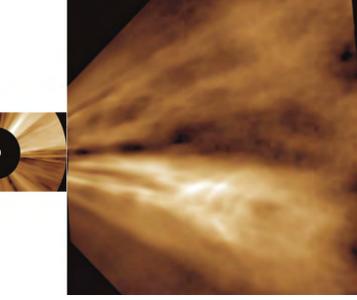
## Mysteries of the Corona-Solar Wind Connection



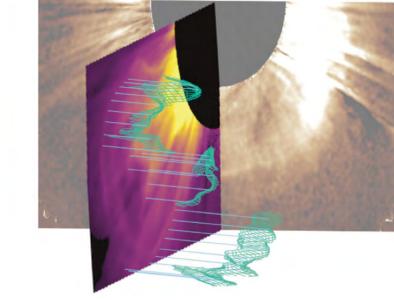
**Detailed structure shapes the outer corona and young solar wind:**  
 Recent results from STEREO/COR2 show that the transition to the solar wind is highly structured at all optically resolvable scales. This contrasts with current solar wind models that treat the flow as smooth. With 10x higher sensitivity than COR2, PUNCH reveals how this structure imprints on the solar wind.



**Intermittent structure traces solar wind flow & causes variability at Earth:**  
 Flow in the outer corona is highly variable. Intermittent ejecta may comprise up to 100% of the outflowing plasma. PUNCH is uniquely able to routinely track all of these features in 3D, to trace the origin of the solar wind, identify late-stage acceleration, and determine the role of ejecta in the solar wind as a whole.



**The Alfvén zone and onset of turbulence mark the elusive base of the heliosphere:**  
 The transition from structured coronal flow to isotropic turbulent flow marks the outer boundary of the corona and the inner boundary of the solar wind. The newly-discovered Alfvén zone determines the Sun's open flux budget and shapes the solar wind. PUNCH explores the otherwise inaccessible cross-scale physics of this "discovery space" and the plasma's journey from corona to solar wind.



**Polarized imaging reveals how CMEs and solar wind structures move and evolve in 3D**  
 CMEs and other ejecta are fundamentally 3D objects. Deep-field polarized imaging with PUNCH reveals the 3D details of these structures for the first time, revealing: interior evolution; flux rope chirality (tied to leading-edge Bz); 3D propagation, acceleration and possible deflection; and solar wind interaction of CMEs and ejecta.

PUNCH Mission Profile	
<b>Mission Structure</b>	1+3 constellation of smallsats
<b>Orbit</b>	600km 6am/6pm Sun-synch LEO
<b>Launch</b>	2023 Q1
<b>Duration</b>	2 years (+90 days commissioning)
<b>Spacecraft type</b>	3-axis stable; propulsion for orbit trim
<b>Development Strategy</b>	Spacecraft are interchangeable; each carries one PUNCH camera
<b>Concept of Operations</b>	Full-field imaging, 4 min. cadence (No targeting, no campaigns); Synchronous across constellation
<b>Field of View</b>	All position angles, 1.25°-45° from Sun (90° dia.); NFI: 1.25°-8.0°; WFI: 5°-45°
<b>Wavelength Range</b>	White light (450-750 nm)
<b>Data Products</b>	Full field image mosaics (B and pB) Coronal close-up images (B and pB) Background-subtracted "R" images (B/pB) Solar wind flow maps
<b>Data Distribution</b>	Via VSO and SDAC; open data policy

### PUNCH Instruments

**Narrow Field Imager (NFI): Externally occulted coronagraph**

- Single stage design is simplified compared to STEREO/COR2
- FOV is 1.25° to 8° from Sun
- Polarizing filter wheel behind focusing optics
- Made at NRL (camera: RAL)

**Wide Field Imager (WFI) x3: Heliospheric imager**

- Linear corral baffle design includes lunar rejection features
- FOV is 40° truncated square (5° to 45° from Sun)
- Polarizing filter wheel ahead of focusing optics
- Made at SwRI (camera: RAL)

### PUNCH Science Objectives

- Understand how coronal structures become the ambient solar wind.**
  - Map evolving solar wind flow
  - Identify microstructure and turbulence
  - Locate the Alfvén surface
- Understand the dynamic evolution of transient structures in the young solar wind.**
  - Track CMEs and their evolution in 3D
  - Measure CIR formation & evolution
  - Determine large-scale shock dynamics

## FOV and wind maps One "virtual instrument", 4 cameras

**Global images for context & completeness**

Understanding the young solar wind requires global images of the inner heliosphere. The PUNCH FOV extends from the mid corona to 45° from the Sun at all solar position angles, including high latitudes that are now completely unobserved.

**Multiple Instruments**

Across the PUNCH FOV, the corona and solar wind brightness varies by over 1,000x. This dynamic range requires two instrument types: a narrow-field imager (NFI) coronagraph similar to STEREO/COR2 and a wide-field imager (WFI) similar to STEREO/HI. The instruments are matched in wavelength and are operated asynchronously to yield a single well-defined field of view.

**Sensitivity and Exposure Time**

Current heliospheric imagers are not limited by photon statistics, but by the quality of starfield subtraction - which is limited in STEREO/HI, by non-linearities in the light imaging system. PUNCH exploits this by making shorter exposures in the heliosphere.

**PUNCH maps solar wind flow and acceleration at all azimuths, out to 100 Rs, every few hours.** Global solar wind measurement is critical for understanding late-stage wind acceleration and the large- and cross-scale interplay between coronal physics and solar wind conditions.

**Observing Geometry: 1 NFI + 3 WFIs**

PUNCH is a constellation of four smallsats distributed around Sun-synchronous twilight orbit. In this geometry, the Sun is always near the horizon. NFI looks directly at the Sun (blocked by its occulting disk), and WFI looks between the Sun and the zenith. A spacecraft roll program maintains Earth behind the baffle plane of each WFI instrument.

**A Composite Field of View**

PUNCH assimilates data from multiple cameras to produce global images of the inner heliosphere. Inside 80 Rs (blue circle) is sampled every few minutes. Outside 80 Rs and inside 45° (green circle), the complete FOV is sampled 6 times per orbit. Frames are co-aligned to 40.1° pixel with optimized resampling and starfield-derived pointing.

## 3D imaging via polarization

**Polarization for precise 3-D imaging**

PUNCH measures the location and shape of ejecta in 3D using deep-field imaging and the polarization physics of Thomson scattering. This image from STEREO/COR2 demonstrates the technique, but 3x-10x lower noise levels are required for routine polarimetric location of blobs, puffs, and features within CME cores.

**Overcoming the limits of stereoscopy**

Stereoscopic imaging from two vantage points is limited in the extended, optically thin context of solar wind imaging. In particular, the "leading edge" of a CME or CIR is different from different vantage points, spoiling the stereoscopic inversion. PUNCH overcomes this difficulty with single-vantage 3D measurement of CMEs, CIRs, shocks, and small ejecta.

**CME Trajectory**

Extended objects such as CMEs are compact along the line of sight near the bright leading edge, due to the Mean Value Theorem. PUNCH locates the leading edge of CMEs directly in 3D by analytic inversion, and characterizes the 3D structure and trajectory using forward modeling and fitting. PUNCH trajectory analysis is sensitive enough to detect expected effects such as acceleration, deceleration, and deflection by the ambient solar wind.

**CME Chirality**

With sufficient signal-to-noise ratio (SNR), it is possible to measure the chirality of a CME, using density traces to follow the magnetic field. This demonstration uses a forward model of two similar flux rope CMEs with opposite chirality, launched from a model Sun at 45° from the sky plane. Measuring chirality is a key step toward prediction of Bz - a critical measure of CME geoeffectiveness. PUNCH will demonstrate this technique.

## How PUNCH Reveals 3D Structure

**A: Thompson Scattering Polarizes Light**

Light carries an electric field. An electron, which re-radiates as a dipole antenna, scatters light perpendicular to the plane formed by the Sun, the Observer, and the scattering electron (Mimant, 1930). The brightness (B) which depends on the square of the electric field, has two components: radial polarization (B<sub>r</sub>) and tangential polarization (B<sub>t</sub>). The polarization ratio is PR = B<sub>t</sub>/B<sub>r</sub> = cos²θ, so 3-axis stereoscopy. This is exact if we assume the Sun is a point source - appropriate for heights > 2.16 Rs. PR can also be written in terms of the observed degree of polarization: PR = (1 - p)/(1 + p), where p is the degree of polarization and p = B<sub>t</sub>/B<sub>r</sub> (Panel E).

**D: Demonstration with ENLIL: CME Location**

ENLIL-modified CME crosses (B) Forward model of PUNCH observations (C) Derived CME trajectory in the sky plane (non-impacting) (D) Actual trajectory (E) CME location (F) CME location (G) CME location (H) CME location (I) CME location (J) CME location (K) CME location (L) CME location (M) CME location (N) CME location (O) CME location (P) CME location (Q) CME location (R) CME location (S) CME location (T) CME location (U) CME location (V) CME location (W) CME location (X) CME location (Y) CME location (Z) CME location (AA) CME location (AB) CME location (AC) CME location (AD) CME location (AE) CME location (AF) CME location (AG) CME location (AH) CME location (AI) CME location (AJ) CME location (AK) CME location (AL) CME location (AM) CME location (AN) CME location (AO) CME location (AP) CME location (AQ) CME location (AR) CME location (AS) CME location (AT) CME location (AU) CME location (AV) CME location (AW) CME location (AX) CME location (AY) CME location (AZ) CME location (BA) CME location (BB) CME location (BC) CME location (BD) CME location (BE) CME location (BF) CME location (BG) CME location (BH) CME location (BI) CME location (BJ) CME location (BK) CME location (BL) CME location (BM) CME location (BN) CME location (BO) CME location (BP) CME location (BQ) CME location (BR) CME location (BS) CME location (BT) CME location (BU) CME location (BV) CME location (BW) CME location (BX) CME location (BY) CME location (BZ) CME location (CA) CME location (CB) CME location (CC) CME location (CD) CME location (CE) CME location (CF) CME location (CG) CME location (CH) CME location (CI) CME location (CJ) CME location (CK) CME location (CL) CME location (CM) CME location (CN) CME location (CO) CME location (CP) CME location (CQ) CME location (CR) CME location (CS) CME location (CT) CME location (CU) CME location (CV) CME location (CW) CME location (CX) CME location (CY) CME location (CZ) CME location (DA) CME location (DB) CME location (DC) CME location (DD) CME location (DE) CME location (DF) CME location (DG) CME location (DH) CME location (DI) CME location (DJ) CME location (DK) CME location (DL) CME location (DM) CME location (DN) CME location (DO) CME location (DP) CME location (DQ) CME location (DR) CME location (DS) CME location (DT) CME location (DU) CME location (DV) CME location (DW) CME location (DX) CME location (DY) CME location (DZ) CME location (EA) CME location (EB) CME location (EC) CME location (ED) CME location (EE) CME location (EF) CME location (EG) CME location (EH) CME location (EI) CME location (EJ) CME location (EK) CME location (EL) CME location (EM) CME location (EN) CME location (EO) CME location (EP) CME location (EQ) CME location (ER) CME location (ES) CME location (ET) CME location (EU) CME location (EV) CME location (EW) CME location (EX) CME location (EY) CME location (EZ) CME location (FA) CME location (FB) CME location (FC) CME location (FD) CME location (FE) CME location (FF) CME location (FG) CME location (FH) CME location (FI) CME location (FJ) CME location (FK) CME location (FL) CME location (FM) CME location (FN) CME location (FO) CME location (FP) CME location (FQ) CME location (FR) CME location (FS) CME location (FT) CME location (FU) CME location (FV) CME location (FW) CME location (FX) CME location (FY) CME location (FZ) CME location (GA) CME location (GB) CME location (GC) CME location (GD) CME location (GE) CME location (GF) CME location (GG) CME location (GH) CME location (GI) CME location (GJ) CME location (GK) CME location (GL) CME location (GM) CME location (GN) CME location (GO) CME location (GP) CME location (GQ) CME location (GR) CME location (GS) CME location (GT) CME location (GU) CME location (GV) CME location (GW) CME location (GX) CME location (GY) CME location (GZ) CME location (HA) CME location (HB) CME location (HC) CME location (HD) CME location (HE) CME location (HF) CME location (HG) CME location (HH) CME location (HI) CME location (HJ) CME location (HK) CME location (HL) CME location (HM) CME location (HN) CME location (HO) CME location (HP) CME location (HQ) CME location (HR) CME location (HS) CME location (HT) CME location (HU) CME location (HV) CME location (HW) CME location (HX) CME location (HY) CME location (HZ) CME location (IA) CME location (IB) CME location (IC) CME location (ID) CME location (IE) CME location (IF) CME location (IG) CME location (IH) CME location (II) CME location (IJ) CME location (IK) CME location (IL) CME location (IM) CME location (IN) CME location (IO) CME location (IP) CME location (IQ) CME location (IR) CME location (IS) CME location (IT) CME location (IU) CME location (IV) CME location (IW) CME location (IX) CME location (IY) CME location (IZ) CME location (JA) CME location (JB) CME location (JC) CME location (JD) CME location (JE) CME location (JF) CME location (JG) CME location (JH) CME location (JI) CME location (JJ) CME location (JK) CME location (JL) CME location (JM) CME location (JN) CME location (JO) CME location (JP) CME location (JQ) CME location (JR) CME location (JS) CME location (JT) CME location (JU) CME location (JV) CME location (JW) CME location (JX) CME location (JY) CME location (JZ) CME location (KA) CME location (KB) CME location (KC) CME location (KD) CME location (KE) CME location (KF) CME location (KG) CME location (KH) CME location (KI) CME location (KJ) CME location (KK) CME location (KL) CME location (KM) CME location (KN) CME location (KO) CME location (KP) CME location (KQ) CME location (KR) CME location (KS) CME location (KT) CME location (KU) CME location (KV) CME location (KW) CME location (KX) CME location (KY) CME location (KZ) CME location (LA) CME location (LB) CME location (LC) CME location (LD) CME location (LE) CME location (LF) CME location (LG) CME location (LH) CME location (LI) CME location (LJ) CME location (LK) CME location (LL) CME location (LM) CME location (LN) CME location (LO) CME location (LP) CME location (LQ) CME location (LR) CME location (LS) CME location (LT) CME location (LU) CME location (LV) CME location (LW) CME location (LX) CME location (LY) CME location (LZ) CME location (MA) CME location (MB) CME location (MC) CME location (MD) CME location (ME) CME location (MF) CME location (MG) CME location (MH) CME location (MI) CME location (MJ) CME location (MK) CME location (ML) CME location (MN) CME location (MO) CME location (MP) CME location (MQ) CME location (MR) CME location (MS) CME location (MT) CME location (MU) CME location (MV) CME location (MW) CME location (MX) CME location (MY) CME location (MZ) CME location (NA) CME location (NB) CME location (NC) CME location (ND) CME location (NE) CME location (NF) CME location (NG) CME location (NH) CME location (NI) CME location (NJ) CME location (NK) CME location (NL) CME location (NM) CME location (NO) CME location (NP) CME location (NQ) CME location (NR) CME location (NS) CME location (NT) CME location (NU) CME location (NV) CME location (NW) CME location (NX) CME location (NY) CME location (NZ) CME location (OA) CME location (OB) CME location (OC) CME location (OD) CME location (OE) CME location (OF) CME location (OG) CME location (OH) CME location (OI) CME location (OJ) CME location (OK) CME location (OL) CME location (OM) CME location (ON) CME location (OO) CME location (OP) CME location (OQ) CME location (OR) CME location (OS) CME location (OT) CME location (OU) CME location (OV) CME location (OW) CME location (OX) CME location (OY) CME location (OZ) CME location (PA) CME location (PB) CME location (PC) CME location (PD) CME location (PE) CME location (PF) CME location (PG) CME location (PH) CME location (PI) CME location (PJ) CME location (PK) CME location (PL) CME location (PM) CME location (PN) CME location (PO) CME location (PP) CME location (PQ) CME location (PR) CME location (PS) CME location (PT) CME location (PU) CME location (PV) CME location (PW) CME location (PX) CME location (PY) CME location (PZ) CME location (QA) CME location (QB) CME location (QC) CME location (QD) CME location (QE) CME location (QF) CME location (QG) CME location (QH) CME location (QI) CME location (QJ) CME location (QK) CME location (QL) CME location (QM) CME location (QN) CME location (QO) CME location (QP) CME location (QQ) CME location (QR) CME location (QS) CME location (QT) CME location (QU) CME location (QV) CME location (QW) CME location (QX) CME location (QY) CME location (QZ) CME location (RA) CME location (RB) CME location (RC) CME location (RD) CME location (RE) CME location (RF) CME location (RG) CME location (RH) CME location (RI) CME location (RJ) CME location (RK) CME location (RL) CME location (RM) CME location (RN) CME location (RO) CME location (RP) CME location (RQ) CME location (RR) CME location (RS) CME location (RT) CME location (RU) CME location (RV) CME location (RW) CME location (RX) CME location (RY) CME location (RZ) CME location (SA) CME location (SB) CME location (SC) CME location (SD) CME location (SE) CME location (SF) CME location (SG) CME location (SH) CME location (SI) CME location (SJ) CME location (SK) CME location (SL) CME location (SM) CME location (SN) CME location (SO) CME location (SP) CME location (SQ) CME location (SR) CME location (SS) CME location (ST) CME location (SU) CME location (SV) CME location (SW) CME location (SX) CME location (SY) CME location (SZ) CME location (TA) CME location (TB) CME location (TC) CME location (TD) CME location (TE) CME location (TF) CME location (TG) CME location (TH) CME location (TI) CME location (TJ) CME location (TK) CME location (TL) CME location (TM) CME location (TN) CME location (TO) CME location (TP) CME location (TQ) CME location (TR) CME location (TS) CME location (TT) CME location (TU) CME location (TV) CME location (TW) CME location (TX) CME location (TY) CME location (TZ) CME location (UA) CME location (UB) CME location (UC) CME location (UD) CME location (UE) CME location (UF) CME location (UG) CME location (UH) CME location (UI) CME location (UJ) CME location (UK) CME location (UL) CME location (UM) CME location (UN) CME location (UO) CME location (UP) CME location (UQ) CME location (UR) CME location (US) CME location (UT) CME location (UU) CME location (UV) CME location (UW) CME location (UX) CME location (UY) CME location (UZ) CME location (VA) CME location (VB) CME location (VC) CME location (VD) CME location (VE) CME location (VF) CME location (VG) CME location (VH) CME location (VI) CME location (VJ) CME location (VK) CME location (VL) CME location (VM) CME location (VN) CME location (VO) CME location (VP) CME location (VQ) CME location (VR) CME location (VS) CME location (VT) CME location (VU) CME location (VV) CME location (VW) CME location (VX) CME location (VY) CME location (VZ) CME location (WA) CME location (WB) CME location (WC) CME location (WD) CME location (WE) CME location (WF) CME location (WG) CME location (WH) CME location (WI) CME location (WJ) CME location (WK) CME location (WL) CME location (WM) CME location (WN) CME location (WO) CME location (WP) CME location (WQ) CME location (WR) CME location (WS) CME location (WT) CME location (WU) CME location (WV) CME location (WW) CME location (WX) CME location (WY) CME location (WZ) CME location (XA) CME location (XB) CME location (XC) CME location (XD) CME location (XE) CME location (XF) CME location (XG) CME location (XH) CME location (XI) CME location (XJ) CME location (XK) CME location (XL) CME location (XM) CME location (XN) CME location (XO) CME location (XP) CME location (XQ) CME location (XR) CME location (XS) CME location (XT) CME location (XU) CME location (XV) CME location (XW) CME location (XX) CME location (XY) CME location (XZ) CME location (YA) CME location (YB) CME location (YC) CME location (YD) CME location (YE) CME location (YF) CME location (YG) CME location (YH) CME location (YI) CME location (YJ) CME location (YK) CME location (YL) CME location (YM) CME location (YN) CME location (YO) CME location (YP) CME location (YQ) CME location (YR) CME location (YS) CME location (YT) CME location (YU) CME location (YV) CME location (YW) CME location (YX) CME location (YY) CME location (YZ) CME location (ZA) CME location (ZB) CME location (ZC) CME location (ZD) CME location (ZE) CME location (ZF) CME location (ZG) CME location (ZH) CME location (ZI) CME location (ZJ) CME location (ZK) CME location (ZL) CME location (ZM) CME location (ZN) CME location (ZO) CME location (ZP) CME location (ZQ) CME location (ZR) CME location (ZS) CME location (ZT) CME location (ZU) CME location (ZV) CME location (ZW) CME location (ZX) CME location (ZY) CME location (ZZ)