10/24/2001

Measurements of Resonant Magnetosphere-Ionosphere Coupling — CANOPUS, FAST, SuperDARN Conjunction

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Abstract.

1. Introduction

2. Ground-Based Diagnostics

2.1 All Sky Imager (ASI)

One-minute sequential images from the CANOPUS ASI located at Gillam, Manitoba are used to identify large-scale optical features of the resonance and its epochs of oscillation during the FAST satellite conjunction. The field of view of each 6300-nm filtered image shown in Figure 1 spans 53.7 to 58.7 N geodetic and 261.3 to 270.3 W geodetic.

The primary optical signature of the resonance is a series of brightening and fading auroral arcs. These arcs are most evident in the 6300-nm emissions in Figure 1, but they are also seen with lower intensities in 5577-nm emissions (not shown). The arcs appear to drift westward along L shells, in the direction of arc alignment, through the ASI field of view at Gillam. A smaller northerly drift in the direction normal to arc alignment also occurs.

At least three cycles of arc formation and decay are evident in the sequence shown in Figure 1. Beginning at 0405 UT in Figure 1, a faint arc (Arc 1) protrudes about halfway into the field of view from the eastern edge, aligned more or less along a magnetic L shell (L shell alignment at Gillam is from south of east to north of west). In subsequent images, Arc 1 moves westward along the L shell. At 0419 UT, the faint tail of Arc 1 is just leaving the western edge of Gillam's field of view. At 0407 UT, the leading (western) edge of a second arc (Arc 2) enters the eastern field of view at Gillam, appearing simultaneously with the first arc, about 10 km south of it. Arc 2 also moves to the west with time and becomes brightest around 0417 UT. The very faint eastern tail of Arc 2 appears to be leaving Gillam's western edge of view at about 0430 UT. At 0424 UT, the western edge of a third arc (Arc 3) appears near Gillam's eastern field of view. It appears approximately 30 km south of Arc 2 and repeats the cycle of brightening and drift of the second arc. Its intensity has faded to background level at about 0439 UT and may have separated in the direction of the arc alignment into two distinct structures at about 0436 - 0437 UT.

Of the three arcs, Arc 2 is most prominent in 5477-nm images. Because 6300-nm emissions are indicative of soft electron precipitation (energies less than about 1 keV), whereas 5477-nm emissions are indicative of 1-10 keV electron precipitation, it may be concluded that the Arc 2 is also the most energetic of the three.

For future reference, the FAST overpass occurs during the image taken at 0426 UT. The FAST trajectory, projected to the surface of the earth along IGRF field lines, is within the ASI field of view, near its eastern edge, and is represented approximately in the figure by the yellow arrow. At this time, Arc 2 is fading while Arc 3 is starting to brighten. Both are in Gillam's field of view at this time, and the electron precipitation signatures of both arcs are recorded by FAST. The analysis of FAST data presented below will focus on the in situ features of Arc 3 during this time.

2.2 Meridian Scanning Photometer (MSP)

Data from the 4861 nm, 5577 nm, and 6300 nm MSPs at Gillam are shown in Figure 2 for the time interval 0400 UT to 0530 UT. The vertical axis is in (CANOPUS) eccentric dipole latitude (EDFL). The 4861 nm line is indicative of 20-30 keV ion precipitation [*Samson*, 1994], whereas the 6300 nm and 5577 nm lines are primarily diagnostics of soft and hard electron precipitation, respectively, as noted above.

The three arcs identified in the 6300 nm ASI images are also evident in the 6300 nm MSP images. They appear between 64 and 65 EDFL, from about 0405 UT until 0437 UT. The brightest interval of Arc 2 is also evident in the 5477 nm emission.

The region of intense 4861 nm emissions spanning 63-66 EDFL until 0415 UT, with the higher latitude boundary dropping to 64.5 EDFL at 0415 UT, has been interpreted by *Samson* [1994] as the ion precipitation band of the inner plasma sheet and inner edge of the cross-tail current. The auroral arc signature of the resonance evidently occurs within and near the poleward edge of the intense ion precipitation band, on field lines mapping to a region where the earthward-directed ion pressure gradient in the equatorial magnetosphere is presumably relatively strong.

2.3 Ground-Based Magnetometers

Detrended, high-pass filtered magnetometer deflections recorded at Fort Churchill, Gillam and Pina from 0230 UT to 0600UT on 31 January 1997 are shown in Figure 3a.

The data are sampled at 5 sec intervals with the high-pass filter edge at 0.8 mHz. The X component shown in the figure represents the geomagnetic north (positive) deflection at ground level, corresponding to the toroidal (azimuthal) perturbation above the ionosphere when account is taken of ionospheric screening [*Hughes and Southwood*, 1976].

The dynamic spectrum of the X component of the magnetic deflection recorded at Gillam is shown in Figure 3b, constructed from fast Fourier transforms of 1-hour long, 5-minute stepped time series obtained from Figure 3a. Dominant power in Figure 3b occurs at 1.3 mHz with hints of some harmonic content at 2.8-3.3 mHz. The geomagnetic pulsation activity at 1.3 mHz evidently developed about 1.5 hours earlier at Gillam than the corresponding optical activity.

2.4 HF Ionospheric Radar Backscatter

HF ionospheric backscatter signals from the SuperDARN phased arrays located at Saskatoon and Kapuskasing have been examined for evidence of the resonance. Each array sweeps through 75 range gates in each of 16 beam directions once every 2 minutes. Each range gate projects to a length of 45 km along the beam line-of-sight direction at a nominal scattering altitude of 400 km in the ionosphere. The angular width of the beam is 3.24°.

The HF backscatter data are a measure of the line of sight velocity of F-region ionospheric irregularities and, therefore, the line-of-sight ionospheric plasma bulk velocity. For the radar data to be useful, the scattering region must contain small-scale irregularities of sufficient amplitude to provide a backscatter signal above ground-scatter noise levels. Thus the absence of a backscatter signal may be interpreted in one of three ways: (1) the amplitude of ionospheric irregularities is insufficient to provide a strong backscatter signal; (2) the ionospheric velocity in the scattering region is perpendicular to the line of sight of the radar beam; or (3) the HF signal is totally reflected at the bottomside ionosphere by an enhancement in ionospheric density, thus inhibiting signal access to F-region irregularities.

Evidence for a 1.3 mHz FLR was found in backscatter from beam 15 of the Saskatoon radar during the interval from 0400-0530 UT. Figure 4a shows the inferred line-of-sight ionospheric plasma velocity at range gates 14-19 of beam 15. The AACGM latitude of the scattering volume for each range gate is given on the right of the panel. AACGM latitude for this event is greater than the eccentric dipole latitude used in Figure 2 above by about 3°. The open diamonds represent 2-minute resolution data points where an ionospheric backscatter signal was measured. Data points without significant backscatter or contaminated by ground backscatter are not included (especially noticeable in gates 14, 18 and 19). The solid curves connecting data points are derived from a [????? FRANCES] interpolation algorithm.

The power spectral density for the time series shown in Figure 4a for gates 15-18 are plotted in Figure 4b. A strong signal peak at 1.3 mHz is evident in gate 17. The scattering volume of this range gate projects magnetically to a region near but a little west of

Gillam. There is no evidence of a 1.3 mHz signal in gates 15-16. The large signal at about 1.1 mHz in gate 18 is significantly influenced by interpolating across data gaps in Figure 4a. The weak peaks at 3 mHz and above in gates 15-17 may be the radar signature of the similarly weak, ≈3 mHz signal in the Gillam magnetometer data of Figure 3b.

It may be concluded that the Saskatoon radar recorded a 1.3 mHz signal in ionospheric velocity fluctuations on the L-shell where Gillam optical and magnetic data were simultaneously recording 1.3 mHz fluctuations.

3. FAST Satellite Diagnostics

The orbital path of the FAST satellite across the northern auroral zone, projected to 100 km altitude along IGRF lines, is shown in Figure 5. As noted above, the projected orbital track traversed the eastern portion of the field of view of the Gillam 6300 nm ASI in the image shown in Figure 1 at 04:26:03 UT. The red line in Figure 5 is the projected orbital track; the yellow line indicates the location of the terminator; and the pair of green lines delineates the Feldstein auroral oval. The crosses along the (red) orbital track are 5-minute fiducial markers. The location of the initial cross at 0425 UT shows that FAST is just crossing the equatorward edge of the average auroral oval near 0426 UT. In fact, the statistical oval provides a fairly good context for locations of the auroral features seen in the ground-based optical data described above and for the electron precipitation features measured in situ on FAST. For this auroral crossing FAST is near apogee at an altitude of 4146 km and is near magnetic local time of 22.4 MLT.

Electron and ion energy spectra and dc electric and magnetic field fluctuations measured on FAST provide in situ diagnostics of the FLR. (See *Carlson et al.* [1998] for a FAST instrument and mission overview.) The auroral context for the event to be analyzed in more detail is depicted in Figure 6, which shows FAST data for the entire nightside crossing from the plasmasphere to the polar cap. The top panel plots the ion counts versus energy along the satellite trajectory, integrated over pitch angles 0°-180°; the second panel from top shows ion counts versus pitch angle integrated over energies 0.01-20 keV. The third panel shows electron counts versus energy integrated over pitch angles 0°-180°. The fourth panel down shows electron counts versus pitch angle integrated over energies 0.1-20 keV. The fifth panel is the local field-aligned current carried by electrons with energies exceeding 100 eV. The sixth panel is the spin-axis magnetic deflection (essentially east-west component) with the IGRF model field subtracted. The bottom panel is raw electric field measured by the cartwheeling sphere pair 5-8 in the satellite spin plane. The horizontal axis indicates the universal time (UT), satellite altitude (ALT), magnetic local time (MLT), and eccentric dipole latitude (ILAT) along the satellite track.

The magnetic signature of the resonance observed at Gillam is evident at the FAST altitude as the oppositely directed, electron field-aligned current pair, exceeding 2 $\mu A/m^2$, centered on 04:26:05 UT near the equatorward edge of the auroral oval. Notice that FAST crosses the FLR field-aligned current system in 15 sec, which is much shorter than the 13 minute oscillation period as inferred by ground-based instruments. Therefore, FAST captures essentially an instantaneous snapshot of the FLR elecromagnetic mode structure and associated particle signatures.

Electrostatic shocks and low-frequency electrostatic turbulence accompany the resonance, which is seen to stand in a large-scale region of downward field-aligned current—nominally the statistical Region 2 system of Iijima and Potemra in the premidnight sector. The resonance also occurs near the high latitude boundary of intense, energetic ion precipitation. The region of intense energetic ion precipitation observed equatorward of 62.5° in Figure 6 appears to be the FAST signature of the 4861 nm optical signature of the ion precipitation band in Figure 2. Note that the pitch angle dependent stripes in the second from top panel in Figure 6 are due to penetrating, radiation belt particles.

The electron precipitation region located at 04:26:55 UT in Figure 6 appears to be the remnant signature of Arc 2 observed by the ASI at higher latitude. Both the active Arc 3 (at 04:26:05 UT in Figure 6) and the remnant Arc 2 can be identified in Figure 1 in the snapshots recorded at 04:26:03 and 04:27:03. The FAST data indicate that the dominant electromagnetic signatures of the resonance at the time of the FAST crossing are associated with Arc 2.

Poleward of the remnant Arc 2, from 04:27:10 – 04:28:35 UT, the electron precipitation takes the form of a broad inverted V with a nearly isotropic electron energy distribution outside loss cone. The pitch angle behavior of these central plasma sheet, inverted V electrons contrasts sharply with the up-and down-going suprathermal electrons produced by the resonance. The central plasma sheet inverted V electrons are evidently the field-aligned current carriers for the Region 1 current system associated with the large-scale, east-west magnetic deflection from 04:26:50 – 04:29 UT in Figure 6. The structured electron and ion precipitation poleward of the central plasma sheet is typical of the "boundary plasma sheet" which abuts the polar cap.

FAST data for the time interval 04:25:40-04:26:40 UT surrounding the 50-nT eastward magnetic deflection is expanded in Figure 7. The data format for the top five panels is the same as in Figure 6. The electron precipitation during this interval is interpreted as the 4000-km altitude signature of Arc 3 observed by the ASI during the 04:26:03 UT exposure in Figure 1. Highly field-aligned, upflowing, suprathermal electrons, with a either a temporal or spatial double peak, carry a downward field-aligned current in the equatorward section of the structure (04:25:57-04:26:02 UT) Immediately poleward of this downward current is a somewhat broader upward field-aligned current carried by isotropic inverted V electron precipitation (04:26:02-04:26:08.5 UT) with a more intense superposed distribution of highly field-aligned, downflowing, suprathermal electrons (from 04:26:06.5 – 04:26:10.5). Another region of upflowing suprathermal electrons, with weaker fluxes than in the equatorward section of the structure, occurs poleward of the upward current channel. A conic and/or trapped electron feature is also evident in the electron pitch angle data during the interval 04:26:06-04:26:09 UT.

An upflowing ion beam with streaming energy of a few 100 eV coincides with the electron inverted V region. The ion beam is flanked on its poleward and equatorward sides by low energy ion conics, up to a few tens of eV. The conics appear coincidently with the suprathermal electrons, both up- and down-flowing, although the angular width of the conic is larger in the region of downflowing suprathermal electrons, perhaps indicating a more proximate conic source region.

Dispersed ion features surrounding and overlapping the resonance in the top panels of Figures 6 and 7 are also evident. Events with more energetic ions arriving at higher latitudes (or later times) than the less energetic ions are consistent with a southern hemispheric ion source attributed to upward ion beams accompanying the remnant Arc 2 mentioned above. Such ions were probably produced during an earlier epoch of resonant oscillation when the now remnant Arc 2 was then the most active arc. In this interpretation, ion energy dispersion is produced by earthward convective motion (to lower invariant latitude) of the ion beam.

The bottom three panels in Figure 7 provide additional insights into the FLR electromagnetic structure at the FAST altitude. The satellite spin plane magnetic field (essentially east-west) with the IGRF field subtracted is plotted as the red trace in the third panel from the bottom while the magnetic field obtained by integrating the directly measured electron current is plotted as the green trace in this panel. The two curves may be reconciled by including an unmeasured thermal electron current (below particle detector threshold) in the integral-current field estimate, of magnitude sufficient to produce the Region 2 current system evident in the magnetic deflection shown in Figure 6.

A 200-mV/m electrostatic shock occurs in the equatorward region of upflowing suprathermal electrons at 04:26:01 UT in the second from bottom panel of Figure 7, which shows the spin demodulated electric field component parallel to the satellite velocity vector (essentially northward). Intense low-frequency electrostatic fluctuations up to about 100 mV/m occur in the region of most intense upward field-aligned current.

The bottom panel of Figure 7 shows the power spectral density of the electric field component in the panel above. The yellow line indicates the local proton, IGRF cyclotron frequency. The E-field spectrum in the region of intense, downgoing suprathermal electrons (from 04:26:06.5 – 04:26:10.5) exhibits large-amplitude ion-cycloton fluctuations, superimposed on large-amplitude broadband fluctuations extending down to zero frequency. The low-frequency broadband spectrum is even more intense in the equatorward region of upgoing suprathermal electrons, due largely to the power spectral density of the electrostatic shock. Ion cyclotron waves do not coexist with the shock and upflowing suprathermal electrons at this altitude, although we cannot eliminate the possibility that such waves may be confined to lower or higher altitude sections of the same flux tube.

4. In Situ Wave Analysis

Details of the resonant electromagnetic structure and electron energy flow inferred from FAST are shown in Figure 8. The top panel plots relative ambient electron density obtained from electric field sphere #-# [??? BILL PERIA] operated in Langmuir probe mode. The second and third panels are, respectively, the IGRF subtracted, detrended, satellite spin-axis component of the magnetic field and the detrended electric field projected onto the satellite-translation velocity vector. The angular orientations of the plotted magnetic and electric fields deviate from the east-west and north-south directions, respectively, by only ?? degrees. The bottom two panels are the magnetic field-aligned components of the electron energy flux ($\varepsilon_{||}$) and current density ($J_{||}$), both projected along IGRF field lines to the 100-km reference altitude. Positive $\varepsilon_{||}$ and $J_{||}$ are upward, away from the ionosphere.

The electromagnetic width of the resonance may be taken as the width of its associated field-aligned current perturbation, about 20 seconds or 0.4° ILAT in Figure 8 corresponding to 44.5 km at ground level. This width appears to be consistent with the radar backscatter data in Figure 4b, although the high latitude edge of the FLR inferred from the radar signal is somewhat uncertain. The epoch of oscillation corresponds to an oppositely directed, double-current layer configuration described by *Greenwald and Walker* [1980] (see also discussion below). A third residual (or perhaps incipent) current layer is also noticeable during the interval from 04:26:10 – 04:26:20 in both Figure 8 and the electron spectrograms in Figure 7.

The optical signature of the resonance inferred from FAST electron spectra should be thinner than the electromagnetic signature. If a downward-directed electron energy flux exceeding a few mW/m^2 is taken as a proxy for visible light [*Stenbaek-Nielson et al.*, 1998], FAST predicts an FLR-powered arc of about 10 km, in good agreement with the 6300-nm arc shown in Figure 1 at 0426 UT (most equatorward of the two), which is better resolved in the lower panel of Figure 9.

Fine structure in the form of an electrostatic shock near 04:26:01 in Figure 8, and ion-cyclotron and lower frequency turbulence afterward, also accompany the resonance. A spectral analysis has been performed to examine a possible relationship between this small-scale structure and the large-scale features of the resonance. The top panels in Figure 10a are low-pass filtered time series of the FLR magnetic, electric and electron field-aligned current density measured by FAST. The three traces appearing in the bottom panel of Figure 10a are nondimensional power spectral densities (PSD) in the electric (P_E), magnetic (P_B), and current density ($P_{J_{||}}$) of the corresponding times series shown in Figure 8, and the dash-dot lines show the low-pass filtered spectra that have been used to obtain the filtered signals plotted in the top three panels of Figure 10a. The high-frequency roll-off of the low-pass filter was chosen to pass the dominant low-frequency peak evident in the magnetic PSD. Notice that the zero levels for P_B and P_E have been vertically offset, allowing individual curves to be more easily distinguished in the combined plot.

The large-scale structure of the resonance depicted in Figure 10a is similar to the mode structure described by *Greenwald and Walker* [1980], most closely resembling their

Figure 1d showing unipolar, eastward magnetic and northward electric wave perturbations lying between a pair of opposing field-aligned current layers. Ampere's law provides a self-consistency check on the interpretation of the large-scale signals as satellite Doppler-shifted, spatial features. The peak in $P_{J\|}$ at 0.05 Hz translates into a 100-km wavelength sampled at 5 km/s by the north-south satellite traverse. Ampere's law is then readily verified by using $k_\perp = 2\pi/100$ km and the observed amplitudes, $B_{EW} \approx 40$ nT and $J_\| \approx 2\ \mu A/m^2$, from Figure 10a .

The wave impedance and phase inferred from Figure 10a are consistent with the analysis of *Knudsen et al.* [1992] which provides the following estimate for the altitude-dependent, complex wave impedance:

$$Z(\omega) = \mu_0 \frac{E(\omega)}{B(\omega)} = \mu_0 v_A \frac{1 - \Gamma e^{2i\omega z/v_a}}{1 + \Gamma e^{2i\omega z/v_A}}.$$

The reflection coefficient Γ at the ionosphere is defined as

$$\Gamma = \frac{1 - \mu_0 v_A \Sigma_P}{1 + \mu_0 v_A \Sigma_P}$$

where Σ_P is the height-integrated Pedersen conductivity. At the FAST altitude, $z = 4000$ km where $v_A \approx 4\times10^7$m/s (dominantly protons at $10^7/m^3$, J. McFadden, private communication). For the observed frequency of 1.3 mHz, the phase factor is $2\omega z/v_A \approx 0.0017$ implying (1) that the imaginary part of the impedance at the FAST altitude is negligibly small and (2) that the phase difference between E_{NS} and B_{EW} should be small with B_{EW} leading as observed. With $\exp(2i\omega z/v_A) \approx 1$ one finds $Z(\omega) \approx \Sigma_P^{-1}$ assuming self-consistently that $\mu_0 v_A \Sigma_P >> 1$. The observed wave impedance evaluated from Figure 10a using peak values for E_{NS} and B_{EW} is $Z_{obs} \approx 0.6\ \Omega$. This estimate implies that $\Sigma_P \approx 1.7$ mho, and the phase difference between E_{NS} and B_{EW} can then be estimated as $\phi_B - \phi_E \approx 18°$. This phase difference is consistent with the fields plotted in Figure 10a. A relatively low ionospheric conductivity of 1.7 mho is expected near the equatorward edge of the auroral oval, in the premidnight local-time sector, at low geomagnetic activity [*Hardy et al.*, 1987], matching the conditions of this event.

A band-pass filter has also been applied to the time-series in Figure 9, to isolate the small-scale structure shown in Figure 10b. The band-pass window extends from 0.2−1.5 Hz and is most evident in the bottom panel of Figure 10b as the uppermost dash-dot line representing the product of the P_E and the band-pass filter. Notice that a small band gap from 0.15-0.2 Hz is not included in either the low- or band-pass signals to minimize signal contamination due to satellite spin (5-sec period).

E_{NS} and $J_\|$ are clearly correlated in the small-scale regime. The lack of correlation with B_{EW} is probably due to the limited sensitivity of the FAST magnetometer. The 1 sec width of the 150 mV/m "electrostatic shock" at 04:26:01 UT implies a satellite Doppler width for the shock of $\lambda_\perp \approx 5$ km. Taking $\lambda_\perp$ as the characteristic wavelength of the small-scale shock structure, and using the measured amplitude of 1 μA/m^2 for the field-aligned current in Ampere's law, yields an estimate of 1 nT for the expected magnetic perturbation. This value is less than the uncertainty evident in the magnetic trace of Figure 10b.

Insights into the origin of the 5-km scale shock may be found in the theoretical work of *Lysak and Carlson* [1981], *Lysak and Dum* [1983], *Vogt and Haerendel* [1998], *Lotko et al.* [1998], and *Streltsov and Lotko* [1999], which demonstrate that small-scale, dispersive Alfvén waves are efficiently reflected (reflection coefficient ≈ 1) by collisionless dissipation layers in which $E_{\|} \neq 0$. (The last two cited papers specifically model the 31 Jan 1997 event and include a dissipation layer resulting from FLR-sustained current-driven, ion-cyclotron turbulence and attendant electron momentum drag.) When the lumped behavior of the dissipative layer can be characterized by a simple linear current-voltage relation, $J_{\|} = K\Delta\phi_{\|}$ where $\Delta\phi_{\|}$ is the net field-aligned potential drop across the layer and K^{-1} is the effective resistivity in the layer integrated along its field-aligned extent, *Vogt and Haerendel* show that efficient reflection is expected for Alfvén waves with perpendicular wavenumbers satisfying the implicit relation $2k_{\perp}^2\lambda_t^2 >> 1$. The so-called "transient" length scale λ_t is defined via

$$\lambda_t^{-2} = 2\mu_0 v_A K(1 + k_{\perp}^2 c^2 / \omega_{pe}^2)^{1/2},$$

which includes an electron inertial correction to the original formula derived by *Vogt and Haerendel*.

For the 31 Jan 1997 event, $K \approx 10^{-9}$ mho/m^2 which follows from the observed value of $J_{\|} \approx 1$ μA/m^2 in Figure 10b and the estimate $\Delta\phi_{\|} \approx 1$ kV inferred from the peak electron energization in Figure 7. With $v_A \approx 4\times10^7$m/s and $c/\omega_{pe} \approx 1.7$ km based on a local plasma density of 10^7/m^3, it then follows that $\lambda_t \approx 2$ km. The inequality for efficient Alfvén wave reflection then becomes $\lambda_{\perp}^2 << 8\pi^2\lambda_t^2 \approx 316$ km^2 which is clearly satisfied for the 5-km characteristic wavelength of the shock. The amplitude ratio

$$\frac{E_{NS}}{J_{\|}} = \frac{\mu_0 v_A}{k_{\perp}}(1 + k_{\perp}^2 c^2 / \omega_{pe}^2)^{1/2} \approx 9.4 \times 10^4 \Omega\text{–m}$$

predicted by theory is also comparable to the observed value deduced from Figure 10b.

The large-scale structure of the resonance, determined above to be 100-km in meridonal extent at the FAST altitude, is relatively unaffected by the dissipative layer. At 100 km wavelengths, "transient" length scale effects are negligible ($2k_{\perp}^2\lambda_t^2 << 1$), so the electric field of the large-scale Alfvén wave shown in Figure 10a is impressed, almost fully, on the ionosphere with reflection coefficient Γ given above.

5. Summary

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Figure Captions

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.