Ultraviolet emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter

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Io leaves a magnetic footprint on Jupiter's upper atmosphere that appears as a spot of ultraviolet emission that remains fixed underneath Io as Jupiter rotates[1–3]. The specific physical mechanisms responsible for generating those emissions are not well understood, but in general the spot seems to arise because of an electromagnetic interaction between Jupiter's magnetic field and the plasma surrounding Io, driving currents of around 1 million amperes down through Jupiter's ionosphere[4–6]. The other galilean satellites may also leave footprints, and the presence or absence of such footprints should illuminate the underlying physical mechanism by revealing the strengths of the currents linking the satellites to Jupiter. Here we report persistent, faint, far-ultraviolet emission from the jovian footprints of Ganymede and Europa. We also show that Io's magnetic footprint extends well beyond the immediate vicinity of Io's flux-tube interaction with Jupiter, and much farther than predicted theoretically[4–6]; the emission persists for several hours downstream. We infer from these data that Ganymede and Europa have persistent interactions with Jupiter's magnetic field despite their thin atmospheres.

Emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter are presented in Fig. 1, in ultraviolet images taken with the Space Telescope imaging spectrograph (STIS). The main oval, Io footprints, and polar cap emissions have all been observed in earlier Hubble Space Telescope (HST) images[7,8]. Faint emissions have been observed previously scattered around the auroral oval[7], but the association of these emissions with the satellites can only be established by observing them to remain fixed under the satellites. This was accomplished in a large set of STIS images with high sensitivity and angular resolution obtained between 1998 and 2001. The Ganymede and Europa footprint emissions are indistinguishable from point sources, possibly owing to the limited signal-to-noise ratio. Ganymede's footprint emission appears systematically brighter than Europa's, allowing the measurement of numerous locations of Ganymede's footprint, whereas only a few positions of Europa's have been detected (Fig. 2). Io's footprint emissions at times reach several hundred kilorayleighs (kR) in the measured bandpass ($1\,\mathrm{kR} = 10^9$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ into 4π steradians), corresponding to inputs of tens of $\mathrm{erg\,cm}^{-2}\,\mathrm{s}^{-1}$ assuming an input electron energy of 30 keV (ref. 9). This represents a large local power input to Jupiter's upper atmosphere and ionosphere. The emissions from the Ganymede and Europa footprints are generally a few tens of kilorayleighs in brightness, corresponding to 1–5 erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ or a total power of $1\text{–}5 \times 10^8$ watts (W). This compares with up to 10^{11} W for the brightest Io footprint emissions, and about half that for the total downstream emissions. Callisto's magnetic footprint overlaps the main oval auroral emissions, so comparably bright emissions would not (and have not) been detected.

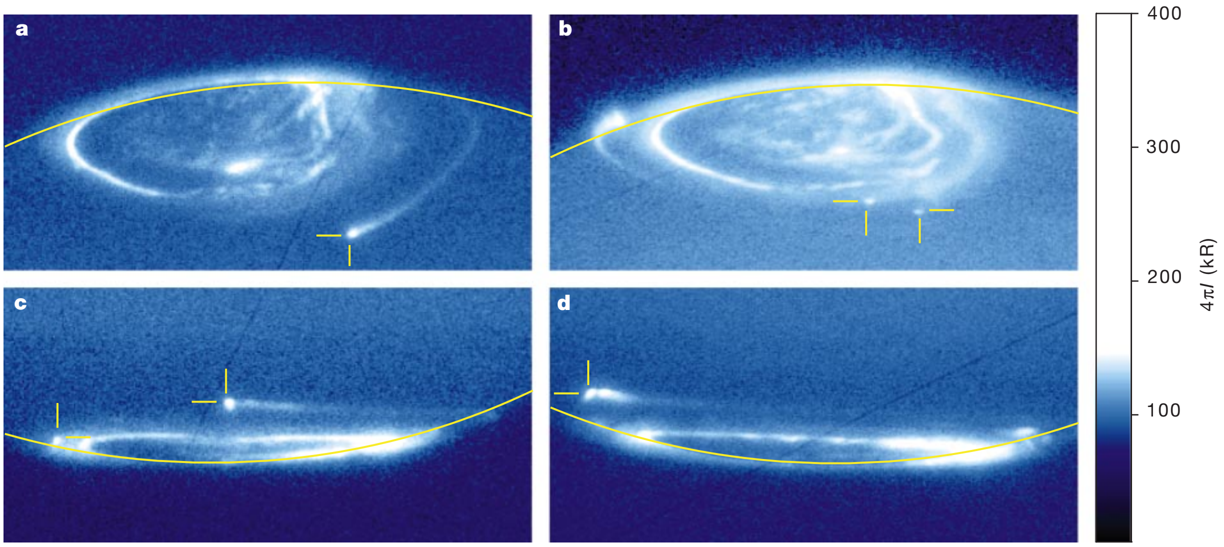

Figure 1 Composite of images with the STIS UV-MAMA (multi-anode microchannel array) of Jupiter's north and south polar regions. **a**, **c**, 20 January 2001; **b**, **d**, 26 November 1998. The central meridian longitudes for these images are: **a**, 156.0; **b**, 164.2; **c**, 41.3; and **d**, 14.0 degrees. The extended ultraviolet emissions from Io's magnetic footprint and wake region mapping into Jupiter's ionosphere are the brightest point sources in each image; in **b**, Io's footprint appears above the left-hand limb. The images have been stretched to emphasize the trailing emissions downstream of Io. Ultraviolet emissions from the magnetic footprints of Europa and Ganymede appear in **b** near the central meridian, and Ganymede's footprint appears in **c** near the left-hand limb, indicated with tick marks. Unfiltered images (25MAMA) have a bandpass from 115–174 nm, with sensitivity to the auroral spectrum including the H_2 Lyman ($B^1\Sigma_u^+ \rightarrow {}^1\Sigma_g^+$) band emissions and part of the Werner ($C^1\Pi_u \rightarrow {}^1\Sigma_g^+$) band series plus the H Lyman α line. All quoted brightnesses and energy deposition rates refer to the flux in this spectral range. The pixel size of 0.024 arcsec provides reasonable sampling of the point spread function of 0.08 arcsec (or 250–300 km on Jupiter); however, the imaging resolution is further degraded by Jupiter's rotation of roughly 1 degree per 100 s. The ability to 'freeze' Jupiter's rotational motion by taking exposures of the order of 100 s with STIS, while still maintaining a limiting detection of 1 kR, provides the highest effective angular resolution and sensitivity obtained on Jupiter's aurora until now, to our knowledge.

Observations of Ganymede's footprint permit a more accurate determination of the distance to which the main oval maps along Jupiter's magnetic field, and thereby the magnetospheric origin of the auroral activity. Earlier identifications of this distance were based on comparison with planetary magnetic field models, which have a large uncertainty when mapped to the middle magnetosphere owing to the strong radial field component from the current sheet. The identification of Ganymede's magnetic footprint equatorward of the main oval demonstrates conclusively that the main oval maps to distances greater than Ganymede's 15 Jupiter radius (R_J) orbital radius, and the higher latitude of the oval suggests distances greater than $20R_J$. The added observation that discrete features in the main oval corotate with Jupiter[7,10] implies a mapping to distances where the plasma nearly corotates, limiting the distance to less than $30R_J$ because plasma in the magnetodisk begins to fall behind corotation with Jupiter's magnetic field at $20–30R_J$. Recent theoretical papers[11–13] identify this region as the source of the main oval auroral emissions. The observed locations of the Ganymede and Europa footprints will also assist in modelling Jupiter's magnetic field[14], in the sense that larger latitudinal separations of the loci of satellite footprints from each other and from the main auroral oval (Fig. 2) correspond to weaker field regions.

In addition to Io's footprints, trails of emission are observed extending like a comet's tail in the downstream direction, corresponding to plasma picked up from Io by Jupiter's corotating magnetic field. At a limiting sensitivity of about 1 kR, we have not detected any emissions extending in the upstream direction from Io. Earlier observations had indicated some east–west structure to Io's footprint emissions[7,15]. With an order of magnitude gain in sensitivity over earlier HST cameras, the STIS images show clearly that Io's footprint emission is much more extended than the mapped

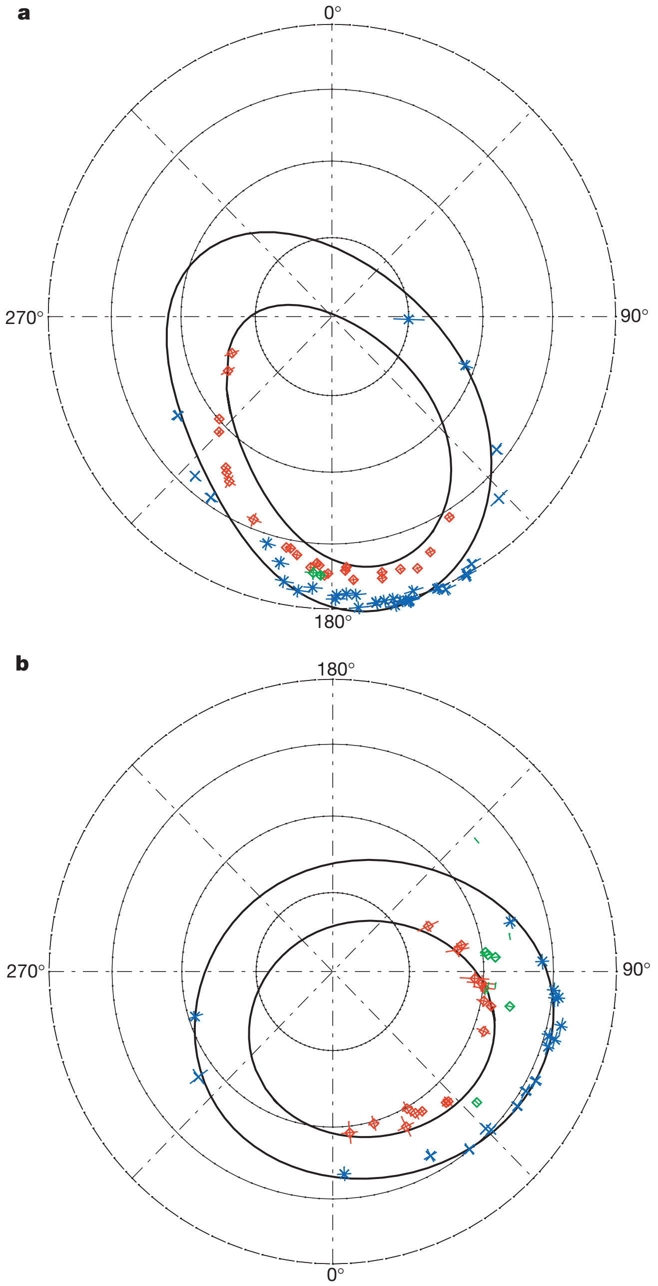

Figure 2 Polar views of north and south auroral zones on Jupiter, showing the observed locations of ultraviolet emissions. The magnetic footprints of Io (blue), Europa (green) and Ganymede (red) are from all STIS images obtained to the end of January 2001. Positional uncertainties are estimated to be 300 and 1,000 km (1 and 3 resolution elements) in the projected distance in the images in the north–south and east–west directions, respectively. **a**, North pole; **b**, South pole. The uncertainties on Jupiter are indicated in this figure by error bars in latitude and longitude. These are generally largest when the emission appears closest to the limb. The overplotted solid lines indicate the mapping from 6 and $30R_J$ in the VIP4 magnetic field model.

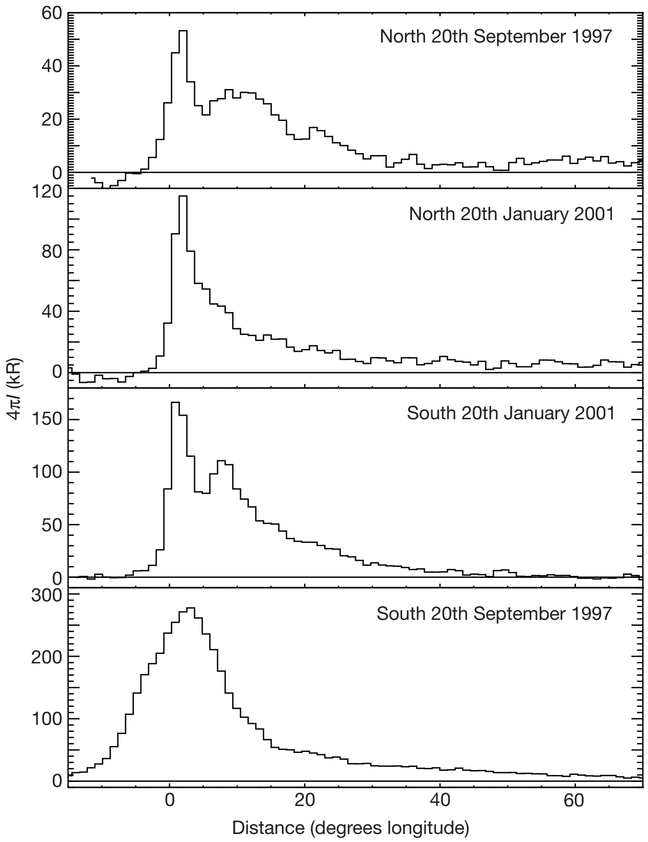

Figure 3 Brightness traces across the ultraviolet footprint emissions of Io in the direction corresponding to the plasma flow, or approximately east–west on Jupiter. The brightness values are based on an assumed 0.014 counts s^{-1} kR^{-1} per 0.08 arcsec resolution element for unfiltered images. The spatial extent is large compared with the magnetic mapping of Io's disk onto Jupiter, at times exhibiting a secondary peak in the downstream direction. In the southern aurora, the footprint emission appears double-peaked in the third panel, the left-hand peak corresponding to Io and the other to a point 1,500 km or 10 Io diameters in the downstream direction from Io for an unperturbed field. Owing to the slowing of field lines in Io's wake, however, both emissions may map to regions near Io (see text). I, intensity into 4π sr.

projection of Io's disk of about 150 km for the unperturbed magnetic field. This finding, consistent with earlier HST images[7], resolves the controversy from a report of a strictly local interaction[3,8] based on lower sensitivity measurements.

Within the measurement uncertainty, the downstream trailing emissions overlap the locus of Io footprints. The combined uncertainties of footprint locations and magnetic field modelling are 1–3° in latitude using the VIP4 model[14], compared with a radial distance of $1R_J$ at Io mapping down to about 2° at Jupiter. This limits our knowledge of the region of the plasma torus to which the trail maps, but it is generally along the orbit of Io. The central peaks commonly appear more extended east–west than north–south, with full widths at half maximum in the range of 500 to 3,000 km. In Fig. 1d, the southern footprint displays two peaks of comparable intensity. Brightness scans (Fig. 3) show the distribution of emissions from a sample of images. A secondary emission maximum in the downstream direction is sometimes, but not always, observed. In the northern images it generally appears fainter than the main peak, while the southern emissions appear brighter overall and at times exhibit an equally bright secondary maximum downstream. We have observed separations of the two maxima up to a few thousand kilometres, corresponding to distances of up to 20 Io diameters when mapped along the magnetic field to Io's orbit.

When we interpret these emissions we take into account the Galileo measurement that the local interaction is driven by mass loading, in contrast with the unipolar inductor process[16]. The measured low flow speed of flux tubes in Io's wake[17] implies that they will carry an initial Alfvenic current and lag behind corotation for 1,200 s after first contacting Io[18]. In the downstream region, the flux tubes are brought back up to corotation. The first and last field lines in this 1,200-s interaction with Io correspond to an interval of 12° of Jupiter's rotation, and the observed secondary maxima extend a comparable distance downstream. We may therefore identify the brightest emissions from Io's footprint, including the secondary maximum, as driven by this interaction region near Io. A more detailed modelling of this process will be required to fully understand this interaction.

Io's downstream emissions extend in the plasma flow direction from the instantaneous magnetic mapping of Io for at least 100° in longitude along the magnetic footprint of Io's orbit. This implies active processes that persist for a few hours after Jupiter's magnetic field has swept past Io. We have considered the possibility of a persistent phenomenon, or afterglow, producing ultraviolet emissions after the direct particle precipitation has ended. However, the ultraviolet emissions result from excited upper states in electronic transitions in H and H_2 which are prompt-decaying and produce radiation in a small fraction of a second. One exception is excitation to the 2*s* state of H, a spin-forbidden transition with a metastable excited state. Ensuing collisions with neutrals can induce radiative decay over a longer timescale; however, a two-photon continuum results from this excited state, limiting the lifetime to seconds[19]. In addition, this process would produce only H Lyα emission, which is inconsistent with the observed bright H_2 spectrum of the downstream emissions. We conclude that the downstream emissions are produced by high-energy charged particles which actively precipitate into Jupiter's atmosphere from the plasma torus downstream of Io, a process continuing at a declining level for several hours after Io has passed.

There are two theoretical frameworks in which the downstream emissions can be interpreted. One is that this emission is produced by plasma stripped from Io but not yet brought up to full corotation. The induction electric field across this plasma could produce a current loop closing in Jupiter's ionosphere, like the interaction at Io itself but with a lower amplitude. The variation in brightness with distance from Io's footprint would then provide an indirect measurement of the rate at which downstream plasma is brought up to corotation. An alternative interpretation[18,20] involves Alfven waves near Io propagating along magnetic field lines, which can reflect from the torus boundaries and also from Jupiter's ionosphere. We can imagine numerous geometries of reflecting Alfven waves propagating downstream, eventually entering the loss cone and producing ultraviolet emissions at Jupiter. This interpretation implies that the downstream ultraviolet emissions could be related to Io's decametric radio arcs[21]. A limitation is that many reflections are needed to extend 100° downstream, and the intensity of any residual waves could decrease to a low level on a shorter spatial scale[20]. We consider the physical process by which the downstream emissions are produced to be uncertain.

To produce ultraviolet emissions from the magnetic footprints of Ganymede and Europa, the initial expectation was for a similar induction process to that occurring at Io but with a smaller amplitude. From the known diameters and orbital distances, plus *in situ* plasma motions from Galileo fly-by measurements, potentials of 100 kV across Ganymede and 150 kV across Europa have been estimated[7]. There is evidence for the modulation of Jupiter's non-thermal radio emissions by Ganymede[22], and the presence of an intrinsic magnetic field and external magnetosphere on Ganymede[23] presents the interesting possibility of continuous magnetic connection between this satellite and Jupiter. Taking the interaction region to be Ganymede's magnetosphere would increase the cross-sectional area and potential by a factor of four[23], comparable to the 400-kV potential across Io. Ganymede's interaction clearly leads to footprint emissions which are considerably brighter than Europa's. Localized ultraviolet emissions from Europa and Ganymede themselves have also been detected, indicating that auroral processes are active at these satellites[24,25] at lower intensities than Io's airglow and auroral emissions. Further observations of the satellite and footprint emissions should establish the connections between them. ☐

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Competing interests statement

The authors declare that they have no competing financial interests.

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A pulsating auroral X-ray hot spot on Jupiter

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Jupiter's X-ray aurora has been thought to be excited by energetic sulphur and oxygen ions precipitating from the inner magnetosphere into the planet's polar regions[1–3]. Here we report high-spatial-resolution observations that demonstrate that most of Jupiter's northern auroral X-rays come from a 'hot spot' located significantly poleward of the latitudes connected to the inner magnetosphere. The hot spot seems to be fixed in magnetic latitude and longitude and occurs in a region where anomalous infrared[4–7] and ultraviolet[8] emissions have also been observed. We infer from the data that the particles that excite the aurora originate in the outer magnetosphere. The hot spot X-rays pulsate with an approximately 45-min period, a period similar to that reported for high-latitude radio and energetic electron bursts observed by near-Jupiter spacecraft[9,10]. These results invalidate the idea that jovian auroral X-ray emissions are mainly excited by steady precipitation of energetic heavy ions from the inner magnetosphere. Instead, the X-rays seem to result from currently unexplained processes in the outer magnetosphere that produce highly localized and highly variable emissions over an extremely wide range of wavelengths.

Observations were made with the high-resolution camera (HRC) of the Chandra X-ray Observatory on 18 December 2000 for an entire 10-h Jupiter rotation (from 10–20 UT) in support of the Cassini fly-by of Jupiter. These observations show strong auroral emissions from high latitudes (Fig. 1) as well as a rather featureless disk that probably results from a combination of reflected and fluoresced solar X-rays[11]. The Chandra data are time-tagged and thus can be mapped into jovian latitude and system III longitude coordinates (system III longitudes are based on the 9.925-hour rotation period of Jupiter's magnetic field). Comparison of the resulting X-ray emission map with simultaneous far-ultraviolet images obtained by the Hubble Space Telescope imaging spectrograph (HST-STIS) shows that the northern auroral X-rays are concentrated in a 'hot spot' within the main ultraviolet auroral oval at high magnetic latitudes (Fig. 2).

The hot spot is located roughly at 60–70° north latitude and 160–180° system III longitude; no similar hot spot is seen in the south, but this is almost certainly due to the poor viewing geometry for the southern polar cap. We note that this same hot-spot region is the site of enhanced infrared emissions from CH_4 (ref. 4), C_2H_2 (ref. 5), C_2H_4 (ref. 6) and C_2H_6 (ref. 7), as well as highly variable H_2 emissions at far-ultraviolet wavelengths[8], and a 'dark spot' in the sunlight reflected from Jupiter at mid-ultraviolet wavelengths[12].

Jupiter's main auroral oval lies at latitudes that map magnetically to radial distances near 30 jovian radii, R_J (refs 13–15); the location of the hot spot at latitudes poleward of the main oval indicates that the bulk of the jovian X-ray emissions must connect along magnetic field lines to regions in the jovian magnetosphere well in excess of $30R_J$ from the planet. The Chandra HRC observations therefore call into question earlier views that attribute the X-ray auroral emissions to energetic particles diffusing planetward from the outer regions of the Io plasma torus and precipitating in the atmosphere at latitudes

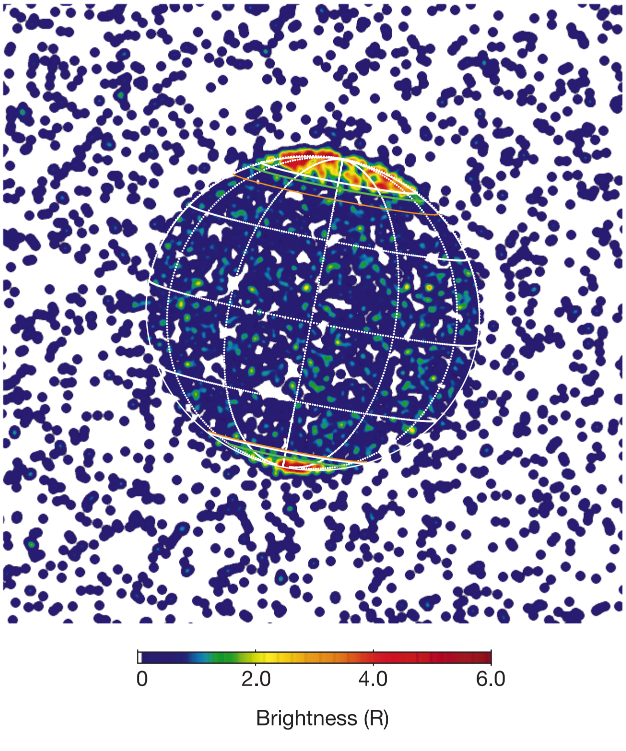

Figure 1 Chandra X-ray Observatory image of Jupiter on 18 December 2000. False colour brightnesses are indicated in rayleighs (*R*). The observation lasted 10 h (10–20 UT) and each X-ray photon has been smeared by double the 0.4-arcsecond full-width half-maximum point-spread-function of the high-resolution camera. A jovicentric graticule with 30° intervals is overplotted, along with the maximum equatorward extent of the $L = 5.9$ (orange lines) and $L = 30$ (green lines) footprints of the VIP4 model[16] magnetosphere. The auroral emissions are located at much higher latitudes than we expected on the basis of previous X-ray observations and indicate a connection with Jupiter's outer magnetosphere. An animation showing the time dependence of these observations may be viewed at http://pluto.space.swri.edu/yosemite/jupiter/ chandra_hrc.html.