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Reports

Molecular Origin of Io's Fast Sodium

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Neutral sodium emissions encircling Jupiter exhibit an intricate and variable structure that is well matched by a simple loss process from Io's atmosphere. These observations imply that fast neutral sodium is created locally in the Io plasma torus, both near Io and as much as 8 hours downstream. Sodium-bearing molecules may be present in Io's upper atmosphere, where they are ionized by the plasma torus and swept downstream. The molecular ions dissociate and dissociatively recombine on a short time scale, releasing neutral fragments into escape trajectories from Jupiter. This theory explains a diverse set of sodium observations, and it implies that molecular reactions (particularly electron impact ionization and dissociation) are important at the top of Io's atmosphere.

IO'S ATMOSPHERE REMAINS ONE OF the least understood in the solar system, despite three spacecraft encounters, extensive ground-based observations and theoretical work (*1, 2*). In addition to uncertain composition, density, and scale height, we do not know if the atmosphere is primarily atoms or molecules. This question is particularly important in the upper reaches of Io's atmosphere near the exobase, where neutrals in the atmosphere react with (and feed) Jupiter's plasma torus. Some work shows that molecules in Io's atmosphere should have dissociated before reaching the top of the atmosphere (*3, 4*), while others suggest that Io's upper atmosphere remains molecular (*5*). Voyager's tentative identification of SO_2^+ (or S_2^+) in the cold inner torus (*6*) suggests that atmospheric escape is molecular, but the Voyager result defies explanation even in the context of the current results (as discussed in the conclusions). The atomic/molecular question is central to understanding how Io's upper atmosphere is replenished, and how mass and energy are supplied to the torus.

Observations of neutral sodium near Io have long been used to probe Io's extended atmosphere [reviewed in (*2*)]. Sodium is only a trace constituent, but its large cross section for resonant scattering of sunlight makes it the most visible emitter. Our sodium cloud images [Figs. 1 (bottom), and 3], distinguish two primary components of the extended sodium atmosphere which arise from different kinematic origins. The first is generated from slow sodium ejected from Io at a few kilometers per second, which forms a banana-shaped cloud curving forward and inside of Io's orbit (*7*). In our images, it always leads Io in its orbit and lies in the orbital plane. The second is created by fast sodium traveling at tens of kilometers per second, and forms intricate and variable jets, fans, or loops on the plane of the sky. Several observers (*8, 9*) have reported sodium traveling at velocities of 30 to 100 km s^{-1}, which they interpreted as originating from charge-exchange reactions in Io's atmosphere. Our recent observations demonstrate that this process cannot reproduce the observed jets or fans. A different process is required, one which bears directly on the atomic/molecular question in Io's upper atmosphere.

We undertook an extensive program of ground-based imaging of ions and neutrals in the Jovian system, using the Catalina Observatory 1.5-m telescope on Mt. Bigelow north of Tucson (*10*). Observations were taken on 26 nights over a 4-month period during the 1989–1990 Jupiter apparition. Our best images of the sodium emissions were obtained on three nights in January 1990 (Table 1). Figure 1 shows typical images of sulfur ions (top, whose motions are governed by magnetic and electric fields) and sodium neutrals (bottom, on gravitational trajectories).

Excellent time coverage has permitted us to characterize the second kinematical component of high-speed sodium. It has a complex and variable structure with repeatable characteristics from night to night. As the figures show, it appears as a jet, fan, or spray of emission extending primarily forward from Io, slightly tilted relative to the orbital and plasma equators. The brightness of the fan at the sodium D_1 line (the fainter D line) is typically several hundred Rayleighs at ~1 R_j (Jovian radius) from Io, comparable to the brightness of the "banana." Changes on time scales much less than an hour suggest that velocities of tens of kilometers per second are required. The width of the jet near Io is just a few arc seconds (or Io diameters). It often exhibits a "hook" whose position corresponds closely to Io's elongation distance, regardless of Io's orbital position. The curved feature that extends around the hook reaches projected heights as much as 2 R_j out of the orbital plane. The emission is not visible within 2 to 3 R_j of Jupiter for a number of reasons (*11*), but it reappears near Io's opposite elongation distance (Fig. 1, left side), where projection effects enhance detectability. Between 6 and 8 R_j, the D_1 emission is more vertically extended, yet still ~200 R (1 Rayleigh = 10^6 photons cm^{-2} s^{-1}); the emission usually peaks well away from the orbital equator. All parts of the feature behave systematically with magnetic longitude, and the section connected to Io is oriented roughly perpendicular to the magnetic field line which passes through Io. The supply rate necessary to maintain the sodium flowing out in the region between 6 and 8 R_j is $\gtrsim 10^{26}$ Na* s^{-1} (fast sodium atoms per second) (*12*). Similar features may have been observed before (*13*) but no attempt at interpretation was made.

Every aspect of the description above can be explained by neutral sodium created through recombination or dissociation of molecular ions injected at Io within the preceding Jupiter rotation (~10 hours).

Table 1. Log of observations. Only images presented in this paper are listed; conclusions are supported by the ~40 other images obtained on these nights, and additional images from other nights. The observation on 10 January was 20 min; those on 11 and 12 January were 10 min. Frame w32340 records S^+, all others image Na (λ_{III} ≡ System III magnetic longitude).

Image number	UT date (1990)	UT start	Orbital longitude	Io λ_{III}	Central meridian λ_{III}
w32143	10 Jan	09:09	187°	122°	129°
w32232	11 Jan	05:30	358°	326°	144°
w32339	12 Jan	06:22	209°	297°	326°
w32340	12 Jan	06:34	211°	302°	333°
w32361	12 Jan	10:27	244°	50°	114°

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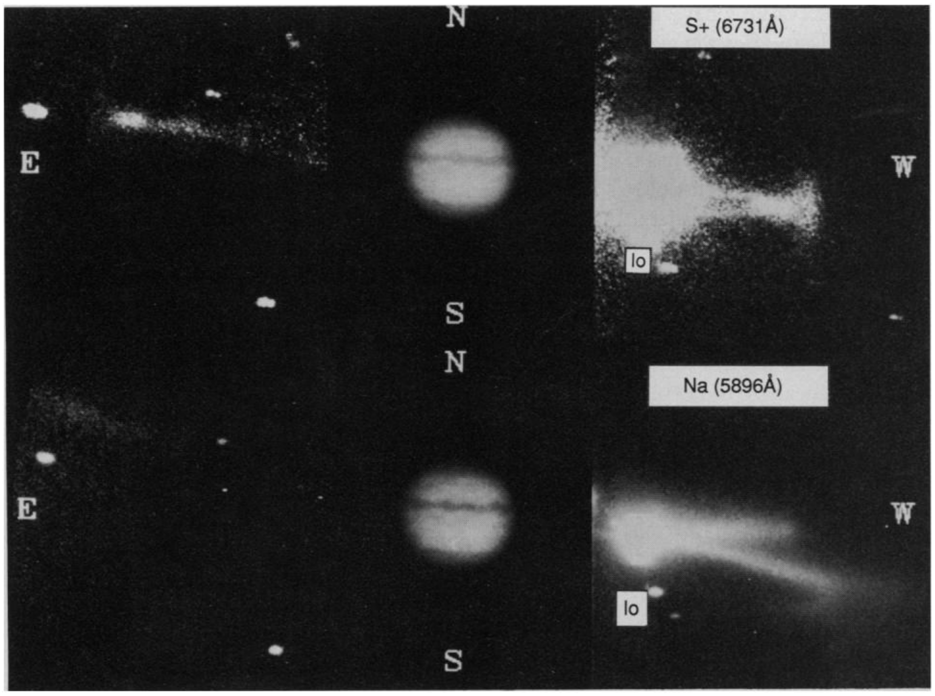

Fig. 1. The top shows emissions from S^+ ions (6731 Å, file w32340) in the plasma torus (confined to the centrifugal equator), and the bottom panel shows neutral sodium emission (D_1 line, 5896 Å, file w32339). The instrument field of view is ~15 R_j wide (1 $R_j \equiv$ 71400 km ≈ 23″). The satellite orbital plane is horizontal. Each "triptych" is a single CCD exposure, but the left and right panels are enhanced differently to show detail, and Jupiter's image in the central panel is exposed through a strip of neutral density gelatin filter which transmits 10^{-4} of the light. Filtering Jupiter's image in this fashion provides unambiguous position registration, intensity calibration, and a reflected image for guiding. The bright spots on the right are a saturated image of Io. Vertical spikes caused by the detector saturation have been eliminated by interpolation. Scattered light from Jupiter has been eliminated by subtracting a radially symmetric high-order polynomial.

These processes match the morphology of the sodium emissions and provide a net local source of fast atomic sodium (necessary to explain the creation of neutral sodium far from the slow sodium "banana"). Other processes still under study may be able to reproduce the same appearance, but this section demonstrates that the selected mechanism is plausible.

The stream of fresh plasma carried downstream from Io does not follow the "centrifugal equator," as the ambient ions do (Fig. 1, top). Ions are typically created away from this plane, and their initial velocities may have some component along the tilted field lines. Therefore the fresh ions will oscillate around the centrifugal equator until damped by collisions (*14*). The stream will be narrow, as the thermal motion of the ions is negligible compared to their motion around Jupiter. Figure 2 illustrates the calculated location of the stream of fresh plasma downstream from Io. The fresh ion stream position is a function of both orbital and magnetic longitudes, so the appearance does not repeat in a simple manner. Figure 3 compares the observed sodium distribution with the fresh ion streams for the three nights of observation. An ion oscillation period of 5.6 hours (solid line) matches the images for all nights. We conclude that the sodium atoms comprising the linear features appearing downstream from Io are generated locally along the stream of ions recently released from Io.

The calculations match the data with a single free parameter: the oscillation period of the fresh ions. The third panel in Fig. 3 shows a significantly better match for 5.6 hours than 4.2 hours (dashed line), a result supported by all 40 frames over the three nights of observation. Cummings *et al.* (*14*) predict a period of 4.2 hours for hot ions (57 km s^{-1} gyrovelocity), and 5.7 hours for low gyrovelocity ions. Our best match of 5.6 ± 0.4 hours may indicate that the plasma flowing past Io slows as it picks up fresh ions. Alternatively, the longer period may be caused by ambipolar electric fields in the plasma (*15*), not included by Cummings *et al.* The small warp observed in the torus (*16*) may affect the ions' equilibrium positions, but will probably not noticeably affect the oscillation period.

Dissociative recombination of sodium-bearing molecules will produce neutral sodium atoms on escape trajectories from Jupiter. The lifetime for this process is approximately 13 hours for assumed torus conditions $n_e = 2000\ cm^{-3}$ and $T_e = 5$ eV (*17*). (We use the example of NaO as a plausible candidate for which rates have been estimated. Most diatomic sodium-bearing molecules have similar rates for electron impact processes.) Recombination of atomic sodium cannot create these features, due to its recombination lifetime of ~100 years (*18*). Dissociative molecular recombination proceeds about 10^5 times faster, primarily because the resulting fragments may take away excess electron energy in the form of translational energy.

Dissociation of the molecular ions will compete with recombination, leaving an ion and a fast neutral fragment. The fast neutral may be a sodium atom; this depends on the type of molecular ion and is not favored in the case of NaO^+. Preliminary calculations suggest that direct dissociation will be faster than dissociative recombination, and therefore may be responsible for the fading of the fast sodium feature around the torus. The observations demonstrate that fast sodium is created up to 8 hours downstream from Io, so the time for loss to dissociation cannot be many times less than this.

The most plausible origin of the molecular ion stream is electron impact ionization [lifetime ~6 hours (*17*)] in Io's atmosphere. The observed rate of ~2 × 10^{26} Na* s^{-1} therefore requires at least this many ionizations per second to occur in Io's atmosphere. (Much more would be required if ions are lost to dissociation without production of fast sodium.) The number of sodium-bearing molecules exposed to electrons is therefore at least $10^{13}\ cm^{-2}$, assuming the exobase lies near the surface; if other molecules are 20 to 100 times more abundant than sodium-bearing molecules, the molecular density must therefore be 2 × 10^{14} to

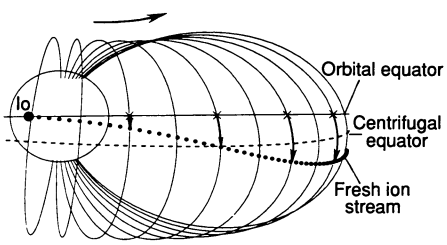

Fig. 2. Motion of ions carried downstream from Io. The dots represent ions picked up by Jupiter's magnetic field and swept to the right. The dashed line shows the centrifugal equator, the equilibrium point of plasma oscillations. Ions originating in Io's atmosphere will begin their oscillation at the intersection of their field line and the orbital equator, marked "X" in the diagram. Ions at the right have therefore completed about half a bounce along the field line.

10^{15} molecules cm^{-2}. Although uncertain to a factor of several, these number are comparable to the entire exospheric column abundance: much of the exosphere must be molecular. More complete modeling is required to determine the full ramifications of electron and ion bombardment of the atmosphere.

Other processes may create fast sodium but cannot reproduce the morphology of the observed streams. The observations require a net local source of neutral sodium within the plasma torus, so processes such as ion-neutral collisions and charge exchange reactions (which basically replace a slow sodium with a fast one) are unsatisfactory. Furthermore, these processes should create broad sprays or fans whose launch velocities are distributed around Io's orbital vector (*19*); such sprays are not evident in our images. We place an upper limit of approximately 5×10^{25} Na^* s^{-1} from charge exchange (*20*).

Schneider (*9*) showed that fast sodium angling out of the orbital plane could be created by a multistep charge exchange reaction (involving atomic sodium) occurring in Io's atmosphere. While this process does mimic the speeds and directions of dissociative recombination in the atmosphere, it cannot explain the observed features beyond a few arc seconds from Io.

Our observations have identified (i) molecular ionization as a major loss process in Io's atmosphere, and (ii) dissociation and dissociative recombination as a new source mechanism for fast sodium atoms. Both of these results have profound implications on the makeup and behavior of Io's atmosphere and Jupiter's magnetosphere.

The presence of significant amounts of sodium-bearing molecules at Io's exobase directly contradicts aeronomical models (*4*), which show its conversion to atomic sodium with a vertical scale height of 1 km. If sodium-bearing molecules reach the top of the atmosphere in great quantities, then SO_2 and other molecules may also arrive intact. Rapid atmospheric blowoff or volcanic activity may be lifting molecules to the exo-base before they can be broken down (*21*).

Other molecular processes may be inferred, in addition to the two required to match the observations. Atmospheric molecules will be dissociated by electron impact, at rates generally faster than ionization. Thus $\gtrsim 2 \times 10^{26}$ sodium atoms per second will be formed, comparable to the rate required to fuel the slow sodium "banana" (*7*). This too is consistent with much or most of the sodium reaching the exobase in molecular form.

Sodium observations provide an unexpectedly clear view of the plasma injection process, and indicate that many ions originally enter the torus in molecular form. Molecular ions do exist in the torus, but only briefly: they are dissociated or they recombine in less than one Jupiter rotation. Most molecular ions form at Io's orbital distance and are lost before moving inwards or outwards, so the Voyager evidence for molecular ions at 5.3 R_j (*6*) remains unexplained.

Dissociative recombination and dissociation may be the primary sources of 800-R_j-wide sodium cloud observed by Mendillo *et al.* (*22*). They concluded that charge exchange reactions provided $\sim 4 \times 10^{26}$ Na^* s^{-1}, even though it required 80 times more sodium in the atmosphere than expected (*17*). Our work reveals (i) no discernible signature of a charge-exchange spray, and (ii) a new process with a supply rate close to the required value. The distant cloud generated by molecular processes would appear quite similar, with the cloud's vertical extent caused by the oscillatory motions of fresh ions, not thermal motions of equilibrated ions. At some level, both processes must contribute; further analysis will determine which process dominates.

The composition of the sodium-bearing molecules remains a mystery. Sodium sulfides have been proposed for the surface, and may be sputtered into the atmosphere (*23*); sodium oxides are also possible. We hope that our conclusions rejuvenate theoretical and laboratory work on the kinds of molecules possible on Io's surface and in its atmosphere. A means must also be found to raise these molecules to the exobase. It is remarkable that the signature of molecular chemistry is so strong that broad conclusions may be reached about the atmosphere and torus without identifying the sodium-bearing molecules.

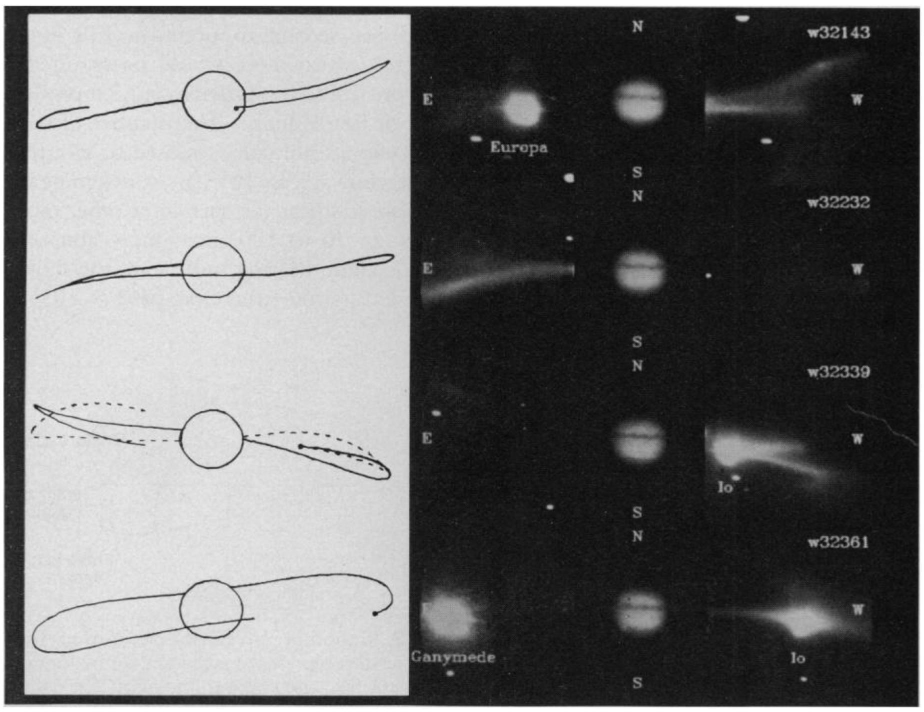

Fig. 3. Comparison of data and calculated fresh ion streams. Frames w32143, w32232, w32339, and w32361 are shown with model calculations. The component of the sodium cloud that lies out of the orbital plane is well matched by the position of the fresh ion stream, implying that these ions are the source of neutral sodium. An oscillation period of 5.6 hours (solid line) is used for all cases. In the third panel, a period of 4.2 hours is also shown (dashed line). For this short period case, note that the "hook" at the west ansa curves north instead of south, and that the model misses the emission east of Jupiter.

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10. The instrument uses narrow-band filters to isolate emissions from specific species and to limit the entrance of scattered light from Jupiter. A Lyot mask eliminates diffraction from the secondary mirror support. The CCD (charge-coupled device) detector is a test version for the Hubble Space Telescope Wide-Field Planetary Camera, and uses a Texas Instruments 800 × 800 pixel chip.
11. Detectability is minimized near Jupiter, due to (i) high-scattered light, (ii) unfavorable projection geometry, and (iii) minimal solar flux for scattering, as the radial velocity relative to the sun (and Fraunhofer lines) is small.
12. The supply of fast sodium atoms in Fig. 1 may be estimated from the flux of atoms crossing a vertical plane seen edge-on approximately 7 R_J west of Jupiter. Sodium will be crossing the plane at 60 km s^{-1} at a wide variety of angles; we assume an average angle of 45°, yielding velocities of ~40 km s^{-1} perpendicular and parallel to the plane. At these velocities, sodium is Doppler-shifted out of the solar Fraunhofer line and will scatter the full continuum intensity. The peak D_1 emission rate at this distance (~300 R) therefore implies a column abundance of 1×10^9 Na cm^{-2}. The fast sodium flux is the product of the peak column abundance, the vertical full-width–half-maximum of the emission (~3 R_J), and the velocity perpendicular to the plane, yielding 9×10^{25} Na* s^{-1}. Recombination ejects sodium at all angles around the torus, some of which will never intersect this selected plane; we estimate the total supply to be double the flux observed at this location, for a total ~2×10^{26} Na* s^{-1}. Until the emissions are better modeled, we consider this number uncertain to a factor of several.
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19. Ions which have equilibrated to the centrifugal equator will corotate in the $\mathbf{\Omega} \times \mathbf{r}$ direction ($\mathbf{\Omega} \equiv$ Jupiter's rotation vector), that is, not strictly perpendicular to **B**. Their thermal motions are non-negligible: charge-exchange products will spray forward into a cone extending about 25° from Io's orbital vector (*22*).
20. The maximum emission attributable to charge exchange (in Fig. 1, for example) is all emission north of the orbital plane between 6.5 to 7.5 R_J west of Jupiter, plus an equivalent amount to the south postulated to underlie the fast sodium released by recombination. The charge exchange supply rate is calculated following the method in (*12*). This upper limit is probably too high, since it assumes no recombination-generated sodium travels north, and that no slow sodium is present in the region.
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24. Interested scientists may obtain one copy of a 5-minute VHS videotape containing movies of the data by sending two blank cassettes (the extra to defray duplication expenses) to the first author. The tape is for illustrative purposes only, and is not to be used for scientific analysis.
25. We gratefully acknowledge A. I. F. Stewart, F. Bagenal, M. McGrath, D. Hunten, J. Richardson, and many members of the International Jupiter Watch for discussion and encouragement. We thank Catalina Observatory (University of Arizona) for extensive use of the telescope. This work has been supported by grants from NASA's Planetary Astronomy and Planetary Atmospheres programs. N.M.S. is supported by the National Science Foundation's Presidential Young Investigator Program.

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The Temperature of Cavitation

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Ultrasonic irradiation of liquids causes acoustic cavitation: the formation, growth, and implosive collapse of bubbles. Bubble collapse during cavitation generates transient hot spots responsible for high-energy chemistry and emission of light. Determination of the temperatures reached in a cavitating bubble has remained a difficult experimental problem. As a spectroscopic probe of the cavitation event, sonoluminescence provides a solution. Sonoluminescence spectra from silicone oil were reported and analyzed. The observed emission came from excited state C_2 (Swan band transitions, $d^3\Pi_g - a^3\Pi_u$), which has been modeled with synthetic spectra as a function of rotational and vibrational temperatures. From comparison of synthetic to observed spectra, the effective cavitation temperature was found to be 5075 ± 156 K.

HIGH-INTENSITY ULTRASOUND provides a unique interaction between energy and matter. As a consequence, sonochemistry and sonoluminescence have been intensely studied over the past few years (*1–5*). Acoustic cavitation is the primary mechanism of sonoluminescence: the nearly adiabatic compression of gas bubbles during cavitation generates enormous local heating (*1, 2, 6–9*). From the calculations of Lord Rayleigh (*10*) through to those of present-day investigators (*6–9*), peak temperatures of thousands of degrees have been predicted, but there has been only limited experimental confirmation (*1, 4, 11, 12*). We have examined the ro-vibronic sonoluminescence of excited state C_2 as a direct probe of cavitation and have used it to determine the effective temperature of cavitation bubble collapse. Our methodology of temperature measurement has been adapted from flame and plasma techniques based on the rotational and vibrational fine structure of diatomic emission spectra (*13*).

For these studies, we have utilized medium-resolution sonoluminescence spectra from excited state C_2. Emission from the Swan bands of C_2 ($d^3\Pi_g - a^3\Pi_u$) is seen from many organic liquids during ultrasonic irradiation under Ar (*12*). For these studies, sonoluminescence from silicone oil was chosen because of its high intensity. Observed sonoluminescence spectra, calculated synthetic spectra, and the resulting difference spectra for the $\Delta\nu = +1$ and $\Delta\nu = 0$ transitions of the Swan bands of C_2 are presented in Figs. 1 and 2, respectively.

The synthetic spectra generated for this work are based on the well-understood theory (*14*) of diatomic-molecule emission. The emission intensity in photons (*I*) of a single rotational line in a ro-vibronic manifold of a diatomic molecule is given in Eq. 1

$$I \propto \nu^4 AS \exp\{(-hc/k)[(G/T_v) + (F/T_r)]\} \quad (1)$$

where ν is the energy of the transition in cm^{-1}, A is the Franck-Condon factor for the vibrational transition, S is the line strength (*15*), G is the energy of the vibrational state, F is the energy of the rotational state above the vibrational state, T_v is the vibrational temperature, and T_r is the rotational temperature. More common methods of calculating spectroscopic temperatures with this equation could not be used because the low intensity of the sonoluminescence permitted only medium resolution with the spectrometer (*16*). Instead, the spectra presented here were modeled with

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