The Astrophysical Journal Letters, 734:L23 (4pp), 2011 June 10 doi:10.1088/2041-8205/734/1/L23

HERSCHEL/HIFI OBSERVATIONS OF HYDROGEN FLUORIDE TOWARD SAGITTARIUS B2(M)

R. R. Monje[1], M. Emprechtinger[1], T. G. Phillips[1], D. C. Lis[1], P. F. Goldsmith[2], E. A. Bergin[3], T. A. Bell[4], D. A. Neufeld[5], and P. Sonnentrucker[6]
[1] California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125-4700, USA; raquel@caltech.edu
[2] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA
[3] Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA
[4] Departamento de Astrofísica, Centro de Astrobiología (CAB), INTA-CSIC, Crta. Torrejón km 4, 28850 Torrejón de Ardoz, Madrid, Spain
[5] Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA
[6] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
Received 2011 April 12; accepted 2011 May 9; published 2011 May 20

ABSTRACT

Herschel/HIFI observations have revealed the presence of widespread absorption by hydrogen fluoride (HF) $J = 1$–0 rotational transition, toward a number of Galactic sources. We present observations of HF $J = 1$–0 toward the high-mass star-forming region Sagittarius B2(M). The spectrum obtained shows a complex pattern of absorption, with numerous features covering a wide range of local standard of rest velocities (-130 to 100 km $^{-1}$). An analysis of this absorption yields HF abundances relative to H_2 of $\sim 1.3 \times 10^{-8}$, in most velocity intervals. This result is in good agreement with estimates from chemical models, which predict that HF should be the main reservoir of gas-phase fluorine under a wide variety of interstellar conditions. Interestingly, we also find velocity intervals in which the HF spectrum shows strong absorption features that are not present, or are very weak, in spectra of other molecules, such as ^{13}CO (1–0) and CS (2–1). HF absorption reveals components of diffuse clouds with small extinction that can be studied for the first time. Another interesting observation is that water is significantly more abundant than hydrogen fluoride over a wide range of velocities toward Sagittarius B2(M), in contrast to the remarkably constant H_2O/HF abundance ratio with average value close to unity measured toward other Galactic sources.

Key words: Galaxy: abundances – ISM: abundances – ISM: individual objects (Sagittarius B2)

1. INTRODUCTION

Hydrogen fluoride (HF) is expected to be the main reservoir of fluorine (F) in the interstellar medium (ISM) because of its unique thermochemistry. Fluorine, predominantly neutral in the diffuse ISM, forms a diatomic hydride molecule with a dissociation energy of 5.87 eV, greater than that of H_2 (4.48 eV). In consequence, fluorine atoms react exothermically with H_2, the dominant constituent of molecular clouds, forming HF. Once the H_2/atomic H ratio exceeds ~ 1, HF becomes the dominant reservoir of fluorine and is destroyed only slowly by photodissociation, with an estimated photodissociation rate of 1.17×10^{-10} s^{-1} for the mean interstellar radiation field, and by reactions with He^+, H_3^+, and C^+. Since HF formation is dominated by reaction of F with H_2, it is expected that the total H_2 and HF column densities track each other closely, with an estimated HF/H_2 abundance ratio within an order of magnitude from 3.6×10^{-8}, when H_2 and HF are the dominant reservoirs of gas-phase H and F nuclei, as shown by Neufeld et al. (2005).

The first detection of interstellar HF was reported by Neufeld et al. (1997) using the Long Wavelength Spectrometer of the *Infrared Space Observatory*. The HF $J = 2$–1 rotational transition was observed in absorption toward the far-infrared continuum source Sagittarius B2 (Sgr B2), at a relatively low spectral resolution ($R = 9600$). However, the need for strong radiative pumping, or extremely high gas density, to populate the HF $J = 1$ level severely limits the utility of HF $J = 2$–1 absorption as a probe of interstellar HF (Neufeld et al. 2005). The HIFI instrument, on board the *Herschel Space Observatory*, has enabled for the first time observations of the *fundamental* $J = 1$–0 rotational transition of HF at 1.232 THz to be performed at high spectral resolution ($R > 10^6$). The line has been detected in environments as diverse as Orion KL, OMC-1 (Phillips et al. 2010), and in diffuse clouds on the line of sight toward W49N, W51 (Sonnentrucker et al. 2010), and W31C (Neufeld et al. 2010). This transition is generally observed in absorption, as expected, due to its very large A-coefficient, $A_{10} = 2.42 \times 10^{-2}$ s^{-1}. Only an extremely dense region, with a strong radiation field, could generate enough excitation to yield an HF feature with a positive frequency-integrated flux (Neufeld et al. 1997). The HF $J = 1$–0 transition promises to be an extremely sensitive probe of the diffuse molecular gas along the line of sight to background far-infrared continuum sources. To date, such material has been studied in the submillimeter regime primarily by means of CO rotational emission lines. However, Neufeld et al. (2005) show in their models that in diffuse clouds of small extinction, the predicted HF abundance can actually exceed that of CO, even though the gas-phase fluorine abundance is four orders of magnitude smaller than that of carbon. HF is a more reliable tracer than CO because the HF/H_2 ratio is constant, whereas CO/H_2 drops in clouds of small A_v (Neufeld et al. 2005). The high A-coefficient of HF $J = 1$–0 results in simple excitation, with essentially all HF molecules being in the ground rotational state under conditions characteristic of the diffuse or even dense ISM. The HF absorption thus traces the total molecular column density along the line of sight, including very cold regions that may not be detectable in CO emission or other commonly used tracers of molecular hydrogen (see, Bergin et al. 2004). HF depletion onto grain mantles has been predicted to occur in high-density regions. The apparent abundance of HF toward Orion KL (Phillips et al. 2010) is much lower compared with that characteristic of diffuse clouds (this may well be due to incomplete coverage of the continuum source by the absorbing material; Orion is an unusual source in that it appears to be heated from the front and therefore does not show absorption,

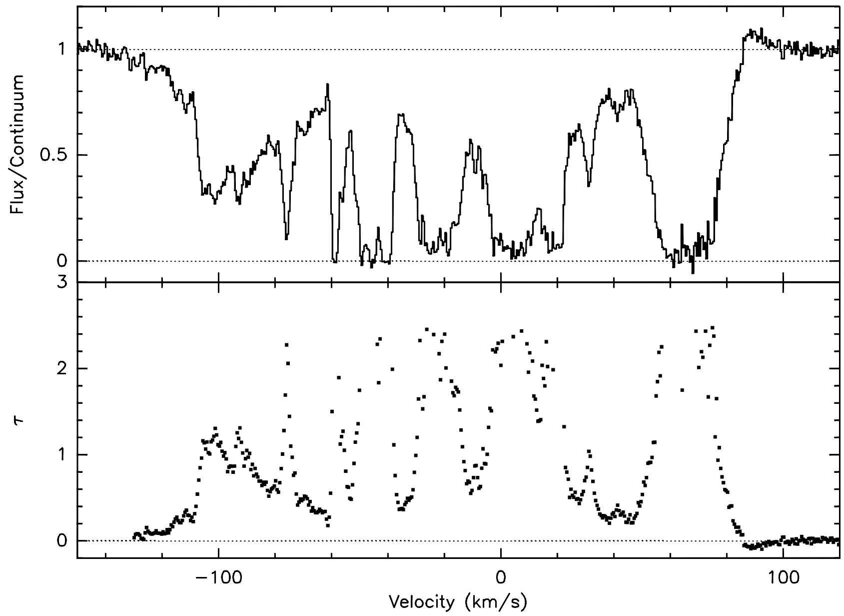

Figure 1. Upper panel: spectrum of the ground-state transition of HF $J = 1$–0 toward Sagittarius B2(M) normalized by the continuum. Lower panel: optical depth (for $\tau \leqslant 2.5$) as a function of LSR velocity.

in general, at submillimeter wavelengths). If we accept that all gas-phase fluorine is in the form of HF, then HF observations can reveal the extent to which volatile species are bound up in icy grain mantles.

In this letter, we report the result of the *Herschel*/HIFI observations of HF $J = 1$–0 toward Sgr B2 as part of the HEXOS (*Herschel*/HIFI observations of extraordinary sources) Guaranteed Time Key Program. Sgr B2 is a very massive (several million solar masses) and extremely active region of high-mass star formation with an extraordinarily rich chemistry, at a projected distance of 100 pc from the Galactic center and at 8.5 kpc from the Sun (Goldsmith et al. 1990). Its strategic location and strong submillimeter continuum flux make Sgr B2 one of the best sources toward which to carry out absorption studies. The Sgr B2(M) line of sight includes essentially the entire path to the center of our Galaxy, allowing us to study simultaneously the physical and chemical conditions of the source itself, Galactic center clouds, and the spiral arm clouds.

2. OBSERVATIONS

The $J = 1$–0 transition of HF with rest frequency 1232.4762 GHz (Nolt et al. 1987) was observed as a part of the full spectral scan of HIFI band 5a toward Sgr B2(M) ($\alpha_{\rm J2000} = 17^{\rm h}47^{\rm m}20\overset{\rm s}{.}350$ and $\delta_{\rm J2000} = -28^\circ 23' 03\overset{''}{.}00$) carried out on 2010 September 16. The dual beam switch observing mode was used with reference beams located 3′ on either side of the source position along an east–west axis. We used the HIFI Wide Band Spectrometer providing a spectral resolution of 1.1 MHz, corresponding to a velocity resolution of 0.27 km $^{-1}$ at the frequency of the HF $J = 1$–0 line, over a 4 GHz intermediate-frequency bandwidth.

The data have been reduced using the *Herschel* Interactive Processing Environment (HIPE; Ott 2010) with pipeline version 5.2. Deconvolution of the double-sideband (DSB) data into a single-sideband (SSB) spectrum has been performed using the standard HIFI deconvolution task (*doDeconvolution*) within HIPE. The resulting Level 2 SSB spectra were exported into FITS format for subsequent data reduction and analysis using the IRAM GILDAS package. Beam observations, reported on 2010 November 17, toward Mars at 1243 GHz give a main beam ($\eta_{\rm mb}$) and an aperture efficiency (η_A) of 0.61 and 0.54, respectively, for the horizontal (H) polarization, and $\eta_{\rm mb} = 0.65$ and $\eta_A = 0.58$ for the vertical (V) polarization. The full width at half-maximum HIFI beam size at the HF $J = 1$–0 frequency is ∼17″.

3. RESULTS

Figure 1 shows the spectrum of the ground-state rotational transition of HF toward Sgr B2(M). The spectrum presents a complex absorption line structure that covers a wide range of local standard of rest (LSR) velocities (−130 to 90 km $^{-1}$) with weak emission tentatively detected at velocities in the range of 90–100 km s^{-1}. In the upper panel of Figure 2 we present, for comparison, the spectrum of the 1_{11}–0_{00} 1113.3430 GHz line of para-water, obtained using HIFI (Lis et al. 2010). The para-water absorption spectrum shows a larger optical depth than that of HF at almost all LSR velocities, in contrast to what has been seen toward other Galactic sources, e.g., W51, W49N, and W31C, where the H_2O/HF abundance ratio is remarkably constant (≈1) and the spectra have similar profiles (Sonnentrucker et al. 2010; Neufeld et al. 2010). In Figure 2 (lower panel) we compare the HF spectrum with ^{13}CO (1–0) and CS (2–1) absorption spectra toward Sgr B2(M) line of sight (observed with the IRAM 30 m telescope; Lis et al. 2001). The ^{13}CO (1–0) and CS (2–1) spectra show absorption components in close correspondence to those seen in the HF absorption spectrum. Most of these absorption features have been attributed to well-known molecular gas clouds along the line of sight toward Sgr B2 (Whiteoak & Gardner 1979; Greaves & Williams 1994). We can distinguish three main velocity intervals. The first interval, with velocities from 35 to 100 km s^{-1}, is mainly dominated by gas associated with the envelope of Sgr B2, which yields broad absorption centered near $\upsilon_{\rm LSR} \sim 64$ km s^{-1}. The second interval, with velocities from −10 to 35 km s^{-1}, shows absorption due to gas within a few hundred parsecs of the Sun, as well as gas within spiral arms at a galactocentric radius ∼5–8 kpc. The third interval, with velocities from −130 to −10 km s^{-1}, shows

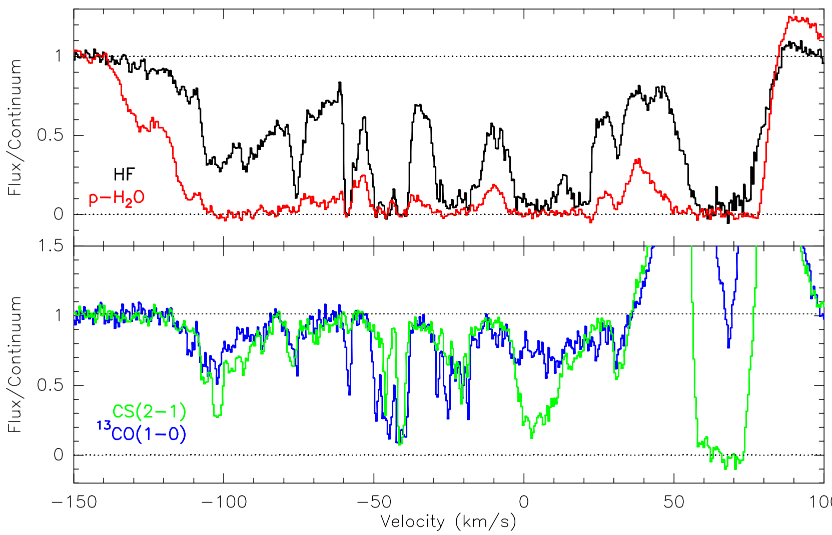

Figure 2. Upper panel: spectra of the ground state of HF $J = 1\text{–}0$ and p-H_2O $J = 1_{11}\text{–}0_{00}$ lines (black and red histograms, respectively) toward Sagittarius B2(M) normalized by the continuum. Lower panel: IRAM 30 m ^{13}CO $J = 1\text{–}0$ and CS $J = 2\text{–}1$ spectra toward the same position (blue and green histograms, respectively).

Table 1
Column Densities of HF and ^{13}CO toward Sagittarius B2(M) and HF Abundances

V_{LSR} (km s^{-1})	N(HF) (cm^{-2})	$N(^{13}CO)$ (cm^{-2})	$N(H_2)^a$ (cm^{-2})	HF/H_2	$N(^{13}CO)/N$(HF)
−115 to −60	9.9×10^{13}	5.7×10^{16}	5.7×10^{21}	1.7×10^{-8}	574
−57 to −53	8.3×10^{12}	2.7×10^{14}	...	...	33
−53 to −49	1.1×10^{13}	6.8×10^{15}	6.8×10^{20}	1.5×10^{-8}	650
−35 to −28	1.3×10^{13}	9.3×10^{15}	9.3×10^{20}	1.4×10^{-8}	706
−18 to −11	2.2×10^{13}	5.3×10^{15}	...	...	236
−10 to −5	1.01×10^{13}	4.8×10^{15}	9.6×10^{20}	1.1×10^{-8}	473
26 to 40	1.7×10^{13}	7.5×10^{15}	1.5×10^{21}	1.1×10^{-8}	445

Note.
[a] The H_2 column densities are calculated based on the ^{13}CO absorption data from Lis et al. (2001), assuming CO abundances of 3×10^{-5} (Sonnentrucker et al. 2007) and a $[^{12}CO/^{13}CO]$ ratio of 60 in the local gas in the Sagittarius arm (−10 to 35 km s^{-1}) and 30 in the remaining velocity intervals (Langer & Penzias 1990). For those intervals with low $N(^{13}CO)/N$(HF) ratio, the assumption of CO fractional abundances of 3×10^{-5} does not apply.

absorption associated with gas located within 1 kpc of the Galactic center (v_{LSR} −130 to −50 km s^{-1}) and in foreground gas at a galactocentric radius 3–5 kpc (−50 to −10 km s^{-1}).

We calculate the HF column densities in the velocities ranges where lines are not saturated. First, we derive optical depths of the HF lines ($\tau = -\ln[1 - T_L/T_C]$, where T_L/T_C is the line-to-continuum ratio), assuming that the foreground absorption completely covers the continuum source and that all HF molecules are in the ground state. We set a conservative lower limit of ∼ln(10) for the optical depth since the observations are not sensitive to larger opacities. The resulting optical depth is shown in Figure 1 (lower panel). We derive the HF column densities for each LSR velocity range using Equation (3) in Neufeld et al. (2010). Table 1 gives the HF column densities in several velocity intervals associated with different molecular clouds. The H_2 column densities in the foreground gas are calculated based on the ^{13}CO absorption data from Lis et al. (2001), assuming a CO fractional abundance for diffuse molecular clouds of $\sim 3 \times 10^{-5}$ (Sonnentrucker et al. 2007) and a $[^{12}CO/^{13}CO]$ ratio of 60 in the local gas in the Sagittarius arm (−10 to 35 km s^{-1}) and 30 for the remaining velocities (Langer & Penzias 1990). In their studies of fluorine chemistry in the ISM, Neufeld & Wolfire (2009) predicted an $N(HF)/N(H_2)$ abundance ratio of 3.6×10^{-8}. Our resultant HF column densities relative to that of H_2 are $\sim 1.3 \times 10^{-8}$, in good agreement with the chemical models. We also calculate the $N(H_2O)/N(HF)$ ratio using the water column densities derived in Lis et al. (2010) in the velocity intervals of −73 to −52 km s^{-1}, −12 to −7 km s^{-1}, and 27 to 35 km s^{-1}. The mean H_2O/HF column density ratio in those intervals is 13.8 with a standard deviation of 0.58. The resulting H_2O/HF ratio is thus significantly higher than that observed toward other submillimeter sources—such as W31C, W49N, and W51—where the H_2O/HF ratio is close to unity and shows a remarkably small dispersion (Neufeld et al. 2010; Sonnentrucker et al. 2010). Our analysis indicates that the HF abundance along the sight line to Sgr B2(M) is similar to that inferred toward the other sources, and that the larger H_2O/HF ratio in Sgr B2(M) reflects an enhanced H_2O abundance along this sight line.

4. DISCUSSION

The observational results shown in Figure 1 reveal HF $J = 1\text{–}0$ absorption over a broad range of LSR velocities along the line of sight toward Sgr B2. The derived abundances of HF with respect to H_2 show a mean of 1.3×10^{-8} with a dispersion of 0.26×10^{-8}. Based on the average gas-phase interstellar abundance in diffuse atomic gas clouds, $N_F/N_H = 1.8 \times 10^{-8}$

(Snow et al. 2007), our observations suggest a small F depletion factor of ∼3 along the line of sight to Sgr B2(M). Neufeld et al. (2010) and Sonnentrucker et al. (2010) estimated similar depletion factors toward G10.6-0.4 and W49N and W51, respectively. These results corroborate the theoretical prediction that HF is the main reservoir of gas-phase fluorine in a wide variety of interstellar conditions where the HF and H_2 column densities track each other closely, with the $N(\mathrm{HF})/2N(\mathrm{H_2})$ ratio equal to the gas-phase elemental abundance of F relative to H. The HF abundance obtained here, which applies to relatively diffuse gas along the sight line to Sgr B2(M), is roughly two orders of magnitude larger than that inferred by Neufeld et al. (1997) from observations of the HF $J = 2$–1 line. This difference is likely explained by the fact that the $J = 2$–1 absorption line probes much denser gas, close to the Sgr B2 core, where the dust radiation field is sufficient to populate the $J = 1$ state of HF; at high densities, the depletion of fluorine onto grain surfaces is likely far more efficient, as recently suggested by Phillips et al. (2010) in their discussion of HF observed toward Orion KL.

The HF spectrum correlates well with the ^{13}CO absorption spectrum. However, a cursory comparison of the two spectra reveals at least two significant features in the HF spectrum, at velocities of -55 km s^{-1} and -15 km s^{-1}, that are not present, or are very weak, in the ^{13}CO data. To our knowledge, the molecular cloud at LSR velocity of ∼-55 km s^{-1} has not been seen in prior molecular absorption line studies. Since the HF/H_2 abundance ratio is independent on A_v (Neufeld et al. 2005), the low $N(^{13}\mathrm{CO})/N(\mathrm{HF})$ ratio for these velocity intervals (see Table 1) indicates that HF is tracing a low-density region having low extinction ($A_v \leqslant 1$) in which the CO abundance drops rapidly due to photodissociation (Lee et al. 1996). Assuming for those molecular clouds a $N(\mathrm{HF})/N(\mathrm{H_2}) = 3.6 \times 10^{-8}$ and using the standard gas-to-dust ratio, $N(\mathrm{H_2})/A_v = 9.4 \times 10^{20}$ molecules cm^{-2} mag^{-1}, to transform visual extinction into molecular hydrogen column density (Frerking et al. 1982), we estimate a visual extinction of the clouds of $\leqslant$0.25 and $\leqslant$0.65 for the -55 and -15 km s^{-1} molecular clouds, respectively. This result is in agreement with the prediction from the chemical model of Neufeld et al. (2005), for which HF abundance in diffuse clouds of small extinction can exceed that of CO, even though the gas-phase fluorine abundance is four orders of magnitude smaller than that of carbon.

Another interesting result is that water is significantly more abundant than HF toward Sgr B2 over a wide range of velocities, in contrast to the remarkably constant H_2O/HF abundance ratio of order unity toward other Galactic sources. The high water abundance was also observed by Neufeld et al. (2000) with their observations of the 1_{10}–1_{01} pure rotational transition of H_2O toward Sgr B2 using the *Submillimeter Wave Astronomy Satellite*, with an average $N(\mathrm{H_2O})/N(\mathrm{H_2})$ of 6×10^{-7}. At LSR velocities associated with gas within 1 kpc of the Galactic center (velocity interval -130 to -10 km s^{-1}), a higher H_2O/HF line ratio has also been observed toward other sources close to the Galactic center, e.g., Sgr A+50 km s^{-1} (P. Sonnentrucker et al. 2011, in preparation).

We thank the referee Dr. Andrew Walsh for his helpful comments and suggestions. HIFI has been designed and built by a consortium of institutes and university departments from across Europe, Canada, and the United States under the leadership of SRON Netherlands Institute for Space Research, Groningen, The Netherlands, and with major contributions from Germany, France, and the US. Consortium members are Canada: CSA, U. Waterloo; France: CESR, LAB, LERMA, IRAM; Germany: KOSMA, MPIfR, MPS; Ireland: NUI Maynooth; Italy: ASI, IFSI-INAF, Osservatorio Astrofisico di Arcetri-INAF; The Netherlands: SRON, TUD; Poland: CAMK, CBK; Spain: Observatorio Astronomico Nacional (IGN), Centro de Astrobiología (CSIC-INTA). Sweden: Chalmers University of Technology-MC2, RSS & GARD; Onsala Space Observatory; Swedish National Space Board, Stockholm University—Stockholm Observatory; Switzerland: ETH Zurich, FHNW; USA: Caltech, JPL, NHSC. Support for this work was provided by NASA through an award issued by JPL/Caltech. This research has been supported in part by the NSF, award AST-0540882 to the CSO. A portion of this research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Facilities: Herschel, IRAM:30m

REFERENCES

Bergin, E. A., Hartmann, L. W., Raymond, J. C., & Ballesteros-Paredes, J. 2004, ApJ, 612, 921
Frerking, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590
Goldsmith, P. F., Lis, D. C., Hills, R., & Lasenby, J. 1990, ApJ, 350, 186
Greaves, J. S., & Williams, P. G. 1994, A&A, 290, 259
Langer, W. D., & Penzias, A. A. 1990, ApJ, 357, 477
Lee, H.-H., Herbst, E., Pineau des Forêts, G., Roueff, E., & Le Bourlot, J. 1996, A&A, 311, 690
Lis, D. C., Keene, J., Phillips, T. G., Schilke, P., Werner, M. W., & Zmuidzinas, J. 2001, ApJ, 561, 823
Lis, D. C., et al. 2010, A&A, 521, L26
Neufeld, D. A., & Wolfire, M. G. 2009, ApJ, 706, 1594
Neufeld, D. A., Wolfire, M. G., & Schilke, P. 2005, ApJ, 628, 260
Neufeld, D. A., Zmuidzidnas, J., Schilke, P., & Phillips, T. G. 1997, ApJ, 488, L141
Neufeld, D. A., et al. 2000, ApJ, 539, L111
Neufeld, D. A., et al. 2010, A&A, 518, L108
Nolt, I. G., et al. 1987, J. Mol. Spectrosc., 125, 274
Ott, S. 2010, in ASP Conf. Ser. 434, Astronomical Data Analysis Software and Systems XIX, ed. Y. Mizuno, K. I. Morita, & M. Ohishi (San Francisco, CA: ASP), 139
Phillips, T. G., et al. 2010, A&A, 518, L109
Snow, T. P., Destree, J. D., & Jensen, A. G. 2007, ApJ, 655, 285
Sonnentrucker, P., Welty, D. E., Thorburn, J. A., & York, D. G. 2007, ApJ, 168, 58
Sonnentrucker, P., et al. 2010, A&A, 521, L12
Whiteoak, J. B., & Gardner, F. F. 1979, MNRAS, 188, 445