Study of Gas Near the Galactic Center Using Infrared Spectra of H_3^+ and CO

Takeshi Oka

773-702-7070

Department of Astronomy and Astrophysics, and Department of Chemistry,
the Enrico Fermi Institute, University of Chicago
t-oka@uchicago.edu

Co-authors

T. R. Geballe, Gemini Observatory, Hilo, HI, USA

Miwa Goto, Max-Planck Institute of Astronomy, Heidelberg, Germany

Benjamin J. McCall, University of Illinois, Urbana-Champaign, IL, USA

Tomonori Usuda, Subaru Telescope, Hilo, HI, USA

Study of Gas Near the Galactic Center Using Infrared Spectra of H_3^+ and CO

1. Gas in the Central Molecular Zone

The central region of our Galaxy contains a super-massive black hole and dense concentrations of stars and interstellar matter (ISM) and shows a variety of extraordinary phenomena due to high energy densities of gravity, magnetic field, X-rays and EUV. The inner region with radius ~ 200 pc, called the Central Molecular Zone (CMZ) (Morris and Serabyn 1996) harbors a vast amount of ISM where hydrogen is dominantly in molecular form. The gas shows high velocity dispersion reflecting the turbulent activities in the area. This region is a small fraction ($\sim 10^{-5}$) of the Galaxy in volume but contains 10 % of the total ISM. Studies of the gas in the CMZ provide information vital for understanding the unusual activities in the central region.

Until recently, three categories of gaseous environments had been known in the CMZ: (1) cold (30 – 100 K) dense ($\geq 10^4$ cm^{-3}) molecular gas observed mostly via radio emission of CO, CS, HCN etc., (2) hot (10^4 – 10^6 K) ionized gas with high electron density (10 – 100 cm^{-3}) observed in recombination and fine structure lines, radio scattering, free-free emission and absorption, and (3) ultra-hot (10^7 – 10^8 K) gas observed in X-rays. These three environments were thought to fill the CMZ (e.g. Fig. 9 of Lazio & Cordes 1998) but recent observations have negated this picture. While each has a high surface filling factor, the volume filling factor f had been overestimated. The value of f for dense gas, thought to be ~ 0.1 (Morris and Serabyn 1996), is more like ~ 0.01 to be in accord with the low color excess (Cotera et al. 2000). For the hot gas, f cannot be very high since the gas is limited to the vicinities of hot stars. For the ultra-hot gas f is also reduced since the Chandra X-ray observations have resolved many X-ray sources as point-like stellar sources rather than extended regions of emission (e.g. Wang et al. 2000; Muno et al. 2003).

There exists abundant gas occupying the CMZ with a significant f that does not belong to any of the above three categories. Analyses of CO radio lines have shown that much of the emission results from gas with low densities of $\sim 10^{2.5}$ cm^{-3} (Oka et al. 1998) and 10^2 – $10^{3.5}$ cm^{-3} (Dahmen et al. 1998). This has become particularly clear from recent studies of the region using H_3^+ which have revealed the existence of a vast amount of warm (~ 250 K) and diffuse (~ 100 cm^{-3}) gas with large cloud dimension (Oka et al. 2005; Goto et al. 2008). Our investigation has just started and will mature in the decade beginning in 2010.

2. Infrared spectra of H_3^+ and CO as astrophysical probe.

We use high-resolution spectroscopy of the ν_2 band of H_3^+ at 3.5 – 4.0 μm (Oka 1980) and the 2 – 0 overtone band of CO at 2.3 μm to study the gas in the CMZ. Compared with radio observations, the infrared observations have the following advantages: (1) since both absorptions are weak (< 20%) and largely optically thin, observed equivalent widths give column densities in each level and allow more direct analyses and (2) the spatial resolution is high since stars in the line of sight to the CMZ are used as continuum sources. The disadvantages are: the observations are limited (1) to the directions toward bright and hot stars with smooth continuum and (2) to gas in front of the background star. The former disadvantage is a serious one but luckily the CMZ has many bright stars to make observations possible, and improved telescope sensitivities are continually expanding the list of suitable stars. The latter disadvantage sometimes is an advantage, as it allows clear discrimination between the foreground and the background gas.

Examples of H_3^+ and CO spectra toward star GCS3-2 of the Quintuplet Cluster are shown in Fig. 1. This star is located close to the Galactic plane and 30 pc to the east of SgrA*. The sharp CO lines at -52, -32, and -5 km s^{-1} (bottom in Fig. 1), are due to cold and dense gas in the foreground spiral arms, 3-kpc (Norma), 4.5-kpc (Scutum) and local arm (Sagittarius), respectively. Those gases are also probed by the H_3^+ $R(1,1)^l$ absorption (top in Fig. 1) as sharp lines.

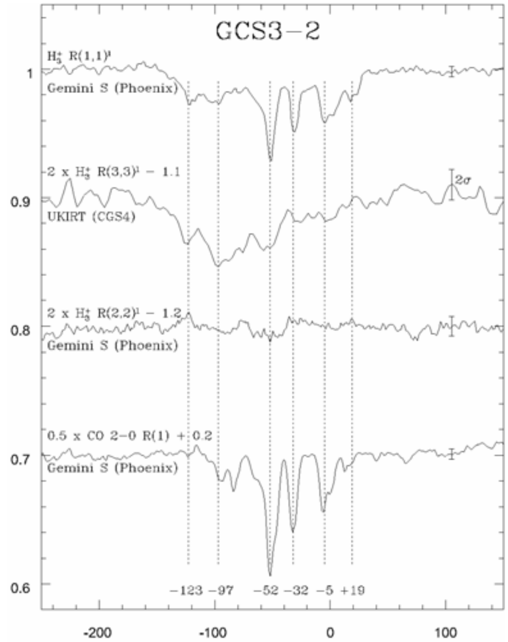

Fig. 1. From the top: The $R(1,1)^l$, $R(3,3)^l$, and $R(2,2)^l$ absorption of H_3^+ and the $R(1)$ line of the 2-0 overtone band of CO toward the brightest star GCS3-2 observed at the Gemini South and UKIRT (Oka et al. 2005).

In contrast, the broad H_3^+ $R(3,3)^l$ line (2nd from the top) represents the warm gas with a high velocity dispersion in the CMZ. The $R(1,1)^l$ absorption, from the lowest $(J, K) = (1,1)$ level shows both sharp lines and a broad "trough,"similar to the $R(3,3)^l$ absorption; we assign the latter to the warm gas in the CMZ. It is noteworthy that the $R(2,2)^l$ absorption (3rd from the top) is very weak indicating a very non-thermal distribution in the (3,3) and (2,2) level.

The rotational energy levels of H_3^+ are shown in Fig. 2. The strong $R(3,3)^l$ absorption demonstrates a high population in the (3,3) level, 361 K above the lowest level, and thus a high temperature for the environment. The weak $R(2,2)^l$ absorption shows a small population in the (2,2) level, which decays to the (1,1) level by spontaneous emission with a life of ~ 1 month (Pan & Oka 1986), and thus low density. *In short, the* $R(3,3)^l$ *line acts as a thermometer and the* $R(2,2)^l$ *line acts as a densitometer.*

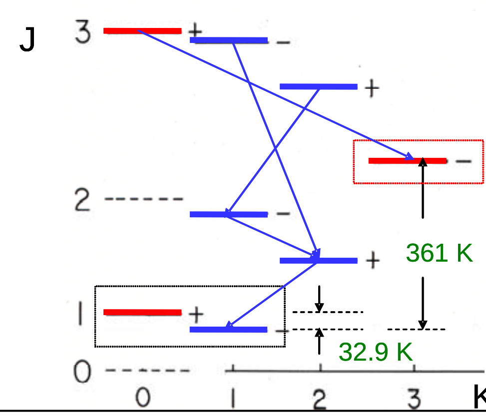

Fig. 2. Rotational levels of the ground state of ortho- (red) and para- (blue) H_3^+. Blue arrows indicate spontaneous emissions (Oka 2006)

A quantitative treatment of H_3^+ thermalization (Oka and Epp 2004) has allowed us to determine temperature T and density n from observed relative column densities of H_3^+ in the (1,1), (2,2), and (3,3) levels.

In addition to temperature T and density n, H_3^+ is unique as a probe in that its simple chemistry provides information on the (cosmic ray) ionization rate ζ in a direct way. It has been shown that ζ in diffuse clouds (on the order of 10^{-16} s^{-1}) is typically10 times higher than in dense clouds (Indriolo et al. 2007) and ζ in the CMZ (10^{-15} s^{-1}) is higher than in diffuse clouds by an additional order of magnitude (Oka et al. 2005; Goto et al. 2008). H_3^+ provides information complementary to that obtained from CO. While CO gives mass of cloud, H_3^+ gives the radial length L of clouds. Together they provide a detailed picture of interstellar clouds.

So far we have observed H_3^+ toward 8 stars all of which are within 3 pc from the Galactic plane and between the core and 30 pc east of it (Fig. 3). All sightlines show high column densities indicating the ubiquity of H_3^+, high ionization rates ζ (on the order of 10^{-15} s^{-1}), and long radial pathlengths (tens of pc) (Goto et al. 2008). The $R(3,3)^l$ absorption indicates high temperature (200 – 300 K), and weak or non-detectable $R(2,2)^l$ absorption demonstrates low density n (50 – 200 cm^{-3}). The sole exception to the latter is the sightline toward GCIRS 3, close to SgrA*, which will be discussed in Section 3.2.1.

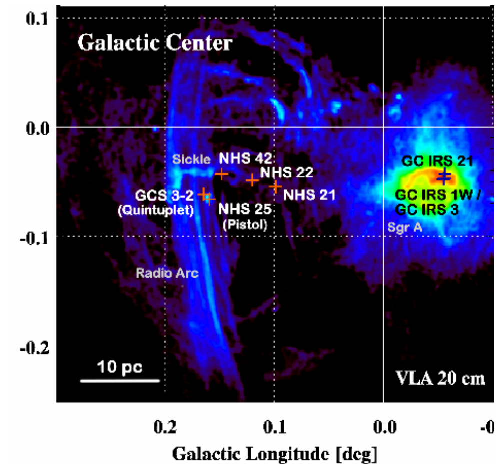

Fig.3 Eight young stars toward which H_3^+ has been observed (Goto et al.2008)

3. The coming decade

In the decade 2010-2020, we will extend the work in two directions. **First** (Section 3.1), we will expand the region to ~ 200 pc to the east and west of the center and from within 3 pc from the Galactic plane to 30 pc increasing the angular area by a factor of ~ 100. The first necessary task is to find hot and bright young stellar objects (YSOs) and other dust-embedded objects suitable for the H_3^+ spectroscopy. This is already being done using medium resolution CO spectroscopy to rule out late type stars as probes; the weak interstellar lines are lost in their complex spectra. Once usable probes are identified, we obtain high-resolution H_3^+ and CO spectra to locate the radial positions of the stars, using the absorptions in the intervening spiral arms as the locating tool. Probes found to be in or behind the CMZ will be used to characterize the properties of the gas in the CMZ. **Second** (Section 3.2), we will examine the central 2 pc with higher spatial and spectral resolution using AO and high resolution spectrometers. The gas in the CMZ in general shows 10 times higher ionization rate compared to the cosmic ray ionization rate in the Galactic disk, but the gas in the central 2 pc appears to be subjected to additional factor of 10 higher ionization rate (Goto et al. 2008).

We will use AO and the IRCS of Subaru, and AO and the CRIRES of the Very Large Telescope (VLT). We will also use the Phoenix Spectrometer on the Southern Astrophysical Research Telescope (SOAR). Some exciting technical developments are anticipated during the decade of 2010. The resolution of the IRCS of Subaru will be increased by ~ 3. For successful execution of this project, it is imperative to have high-resolution infrared spectrometers in the 3 – 4 μm region. Developments of new instruments are eagerly awaited.

3.1. Extending the region of investigation to wider regions of the CMZ

3.1.1 Discriminating young stars from late-type stars

In extending the area of observation by a factor of 100, the first requirement is to find bright and hot stars suitable for the H_3^+ spectroscopy. We have been using the GLIMPSE Point Source

Catalogue provided by the Infrared Array Camera on the Spitzer Space Telescope with photometry at 3.6 (L), 4.5, 5.8, and 8.0 µm (Ramírez *et al*. 2008) and the 2MASS photometry at 1.25 (J), 1.65 (H), and 2.16 (K) µm (Skrutskie *et al*. 2006). In the angular region of interest, which we set to be Galactic longitude $-1.2^{\circ} < \ell < 1.2^{\circ}$ and latitude $-0.2^{\circ} < b < 0.2^{\circ}$ from Sgr A*, we identify in the Catalogue a few thousand stars brighter than $L = 7.5$ mag. Most of these stars are luminous late-type stars (red giants), which have strong and complex absorption spectra by photospheric atoms and molecules, and are not appropriate as the background infrared source for H_3^+ spectroscopy. We exclude them and only retain stars with $J - K$ significantly larger than 5 and/or $K - L$ higher than 1.5. This reduces the number of stars to several hundred. We further reduce the sample by requiring $(J - K)/(K - L) < 2.5$, which largely eliminates red giants suffering more than 30 mag of visual extinction and reduces the number of candidates to a few hundred. We then test the selected stars for suitability using medium resolution CO infrared spectroscopy. Clearly it makes sense to increase the sample by going to fainter magnitudes, assuming the fainter stars can be observed by next generation telescopes and spectrographs.

Medium resolution ($R \sim 10^3$) 1.5 - 2.5 µm spectroscopy using SPEX of NASA IRTF or OSIRIS in SOAR will be conducted to discriminate YSOs and other dust embedded objects from cool late-type stars. Some of the preliminary spectra we obtained at the UKIRT are shown in Fig. 4. The CO overtone bands at 1.5 to 2.5 µm clearly discriminate a young star (left) and a late-type star (right).

.

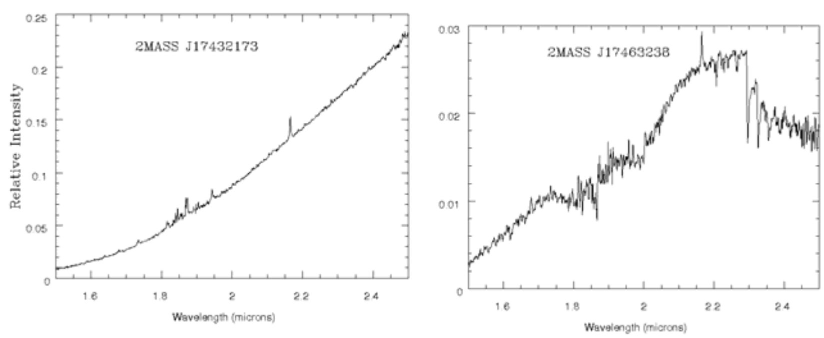

Fig. 4 CO infrared spectra from 1.5 to 2.5 µm. A young and hot star is shown on the left and a red giant on the right. The CO overtone absorption bands at 2.29 µm, 2.32 µm, 2.35 µm, 2.38 µm, etc. clearly discriminate the young and late-type stars.

3.1.2. Locating the Radial Positions of the selected YSOs

Some of the selected young stars will be in the foreground of the CMZ. Their radial location will be determined from high resolution spectra of H_3^+ and CO. As seen in the CO spectrum at of Fig. 1, the CO gas in the foreground spiral arms are clearly marked by the three sharp lines. Those sharp lines allow us to locate the position of a star relative to the spiral arms. Foreground stars are also useful for the H_3^+ spectroscopy since they allow us to clearly discriminate and investigate the gas in individual spiral arms separate from other gas.

Definitive evidence that a star is in or beyond the CMZ is provided by the broad $R(3,3)^l$ line of H_3^+ (second from the top in Fig.1). This line, which starts from the (3,3) rotational level 361 K above the lowest (1,1) level (see Fig. 2) is *the fingerprint* of warm (~ 250 K) and diffuse (~100 cm^{-3}) gas in the CMZ. The spectral line has been observed toward all eight stars in the CMZ surveyed by Goto *et al*. (2008) and nowhere else, and is believed to arise solely there.

Quite apart from its application to H_3^+ spectroscopy, the existence of YSOs in the GC would be in itself an exciting discovery and will be pursued as a spin-off project. The properties of the three known clusters of hot and massive stars in the GC (The Central, Arches, and Quintuplet clusters) indicate that massive star formation occurred in the center several million years ago, but understanding of how such star formation took place in this violent environment in poor. The discovery and study of YSOs in the GC could help solve this riddle. Remarkably the over a dozen *bona fide* YSOs which have given H_3^+ spectra so far are all very close to the Galactic plane. It will be extremely interesting to find out whether this applies to wider regions.

3.1.3 High resolution spectroscopy of H_3^+

For the selected stars, high resolution spectra of H_3^+ and CO will be recorded using the IRCS spectrograph ($R \sim 20{,}000$) on Subaru, the Phoenix spectrometer ($R \sim 60{,}000$) on the SOAR, and CRIRES ($R \sim 100{,}000$) on the VLT. Each of these spectrometer-telescopes has its own strength and weakness. The IRCS on Subaru Telescope is with relatively low resolution and sensitivity, but is very powerful as a survey instrument because of its wide wavelength coverage based on the cross-dispersion grating. There is an ongoing project to make the spectrometer higher resolution. The strength of the Phoenix spectrometer on the SOAR is its high resolution and especially its location in the Southern hemisphere. The CRIRES on the VLT with AO is the most suitable spectrometer at present.

The H_3^+ and CO spectroscopy in the expanded region of the CMZ will provide us the temperature and density of the gas and the value of ζL which will allow us to estimate the volume filling factor and the ionization rate in the wider region of the CMZ. So far our estimate of cloud dimension is along the radial direction but if we can measure wider angular regions of CMZ, we should be able to obtain the transverse dimension which can be more reliably measured. Later, we will extend the observations beyond the edge of the CMZ to find out how the gas density and other gas properties vary as we move off the CMZ. As we increase the investigated region of the CMZ, we will learn more about the morphology of the CMZ.

3.2. Scrutiny of the central region

The central 2 pc of the CMZ is particularly active and the observed H_3^+ spectrum show features that are not seen in other sightlines. Out of the eight sightlines (Fig. 3), the one toward GCIRS 3 of the Central Cluster is unique in that it shows clear $R(2,2)^l$ absorption indicating relatively high density of the gas. This sightline is also exceptional in showing the $R(3,3)^l$ absorption at the velocity of +50 km s^{-1}; for all other sightlines the $R(3,3)^l$ line appear at negative velocities.

3.2.1. GCIRS 3 versus GCIRS 1W

A remarkable aspect of the 50 km s^{-1} gas is that it is visible toward GCIRS 3 but not toward GCIRS 1W which is close to GCIRS 3 in angular distance (Fig. 5). Both stars are thought to belong to the Central Cluster. It is clear that the 50 km s^{-1} gas is on the front side of GCIRS 3 and either on the far side of GCIRS 1W or small enough to miss the sightline toward GCIRS 1W. Similar observation has been reported by Geballe et al. (1989) for CO infrared spectrum.

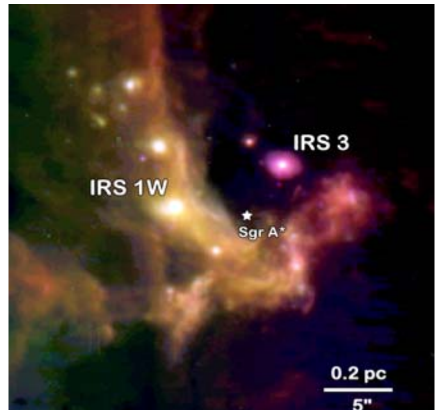

Fig. 5 VISIR N-band three-color view of the Galactic center. From Viehmann et al. (2006).

The velocity of 50 km s^{-1} reminds us of the well known "50 km s^{-1} cloud" near the GC (Brown and Liszt 1984). However, in order to ascribe the newly found gas to this cloud, we need to place GCIRS 3 behind the bulky cloud and thus assume that the angular proximity of the star to SgrA* is a coincidence, a scenario difficult to adopt.

It is well known that high density gas abounds in the central few pc of the GC often in the form of circum-nuclear disks (CNDs). In addition to the elliptic Keplerian ring most clearly observed by HCN (e.g. Christopher et al. 2005), there are other mini-spirals called the Bar, the Northern Arm, and the Eastern Arm (e. g. Lacy et al. 1991); GCIRS 3 is located in the "cavity" formed by the Bar and the Northern and Western Arms and GCIRS 1 is located on the Northern Arm. It is likely that the 50 km s^{-1} observed in the H_3^+ spectrum is due to a compact gas cloud with a dimension of a few tenths pc. Indeed the velocity of 50 km s^{-1} has been reported for HCN radio-emission by Yusef-Zadeh et al. (2008) in the vicinity of GCIRS 3. If we adopt this idea, we need to assume a very high ionization rate ζ on the order of 10^{-14} s^{-1} since the observed high H_3^+ column density gives a high value of ζL and the column length L is at most on the order of 0.5 pc. Such high values of ζ may be reasonable in the central region because of high density of supernova remnants which increase the low energy cosmic ray flux (Yusef-Zadeh et al. 2008) and the intense X-rays and EUV radiation.

3.2.2. Observation of the central 2 pc with high spatial and spectral resolution

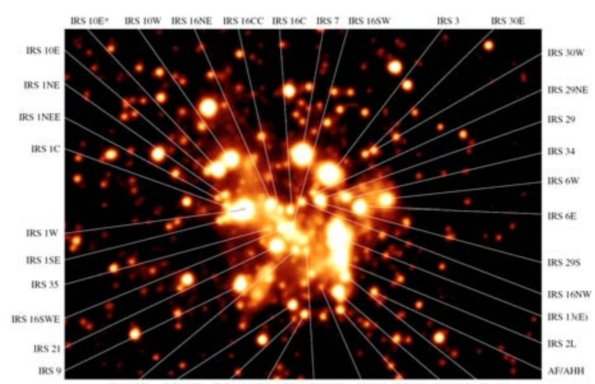

Fig. 6 The ISAAC L-band image of the Galactic center showing most of the named sources (Viehmann et al. 2005)

We will investigate the gas in the central region by the H_3^+ and CO spectra using the AO systems at Subaru and VLT. The region has been studied by H recombination lines, C^+, Ne^+, CO, OH, HCN, HCO^+, NH_3, CS, etc. but H_3^+ probes low density areas with high spatial resolution and provides information complementary to that already obtained. We will use stars in the Central Cluster shown in Fig. 6 as the infrared sources.

We already have some spectra of GCIRS 1W, 3, and 21 at Subaru. We will observe all stars with magnitude brighter than L = 7.5, that is, GCIRS 30W, 29, 12N, 7, 6E, 1SW, 16 NE, 10W, 10E*, 13E, 2L. They may not be hot stars, but it has been our experience that some late-type stars also provide infrared continuum smooth enough for the H_3^+ spectroscopy (e. g. [NHS93] 27).

4. Summary

The infrared spectrum of H_3^+ is a novel astrophysical probe singularly suited to the studies of the gas near the Galactic center. A high fraction of H_3^+ in the Galaxy is concentrated in the CMZ. In spite of its very low number density, H_3^+ in the CMZ is much more readily observed than other hydrogenic probe, H and H_2, and allows general studies of the CMZ, as long as bright and hot stars can be found. H_3^+ provides temperature T, density n, the ionization rate ζ, and radial length of the cloud L; the latter two are unique characteristics of H_3^+.

Our 2010 decadal plan is twofold. (1) We will extend the region of the observation by a factor of 100 covering the bulk of the CMZ. The success of this project depends whether we can find a sufficient number of bright and hot stars in the CMZ. Identifying YSOs in the CMZ is itself an exciting project. (2) We will scrutinize the active central 2 pc region using the bright stars in the Central Cluster. We use AO and high resolution H_3^+ and CO spectroscopy which will lead us to new information which is complementary to one obtained by other methods.

For successful execution of this project, it is imperative to have infrared spectrometers at 3 – 4 μm with resolution of $R \sim 30{,}000$ and higher. Especially if such a spectrometer is operated on a satellite telescope, it will allow us to observe H_3^+ in far away galaxies and exo-planets and revolutionize the field. It is disappointing for us that the planned wavelength of the SPICA mission is limited to higher than 5 μm. Extention of the wavelength to 3 μm is highly desirable.

References

Brown, R. L. & Liszt, H. S. 1984, ARAA, 22, 223
Christopher, M. H., Scoville, N. Z., Stolovy, S. R., & Yun, M. S. 2005, ApJ, 622, 346
Cotera, A. S., et al. 2000, ApJS, 129, 123
Dahmen. G., Hüttemeister, S., Wilson, T.L. & Mauersberger, R. 1998, A&A, 331, 959
Geballe, T. R., Baas, F., & Wade, R. 1989, A&A, 208, 255
Geballe, T. R., McCall, B. J., Hinkle, K. H., & Oka, T. 1999, ApJ, 510, 251
Geballe, T. R. & Oka, T. 1996, Nature, 384, 334
Goto, M., et al. 2008, ApJ, 688, 306
Indriolo, N., Geballe, T. R., Oka, T. & McCall, B. J. 2007, ApJ, 671, 1736
Lazio, T. J. W. & Cordes, J. M. 1998, ApJ, 505, 715
Liszt, H. S., Burton, W. B., & van der Hulst, J. M. 1985, A&A, 142, 237
McCall, B. J., Geballe, T. R., Hinkle, K. H., & Oka, T. 1998, Science, 279, 1910
Morris, M. & Serabyn, E. 1996, ARAA, 34, 645
Muno, M. P., et al., 2003, ApJ, 589, 225
Oka, T., 1980, Phys. Rev. Lett., 45, 531
Oka, T., 2006, Proc. Natl. Acad. Sci. USA, 103, 12235
Oka, T., & Epp, E. 2004, ApJ, 613, 349
Oka, T., Geballe, T. R., Goto, M., Usuda, T., & McCall, B. J. 2005, ApJ, 632, 882
Oka, T., Hasegawa, T., Hayashi, M., Handa, T., & Sakamoto, S. 1998, ApJ, 493, 730
Pan, F.-S. & Oka, T. 1986, ApJ, 305, 518
Viehmann, T., Eckert, A., Schödel, R., Straubmeir, C., & Pott, J.-U. 2005, A&A, 433, 117
Viehmann, T., Eckert, A., Schödel, R., Pott, J.-U., & Moultaka, J. 2006, ApJ, 642, 861
Wang, Q. D., Gotthelf, E. V., & Lang, C. C. 2000, Nature, 415, 148
Yusef-Zadeh, F., Muno, M., Wardle, M., & Lis, D. C. 2007, ApJ, 656, 847