Band 10   Bandwidth and Noise Performance

A Preliminary Design Review of Band 10 was held recently. A question was raised which requires input from the Science side. Here is the key section of the report.

Given the state-of-the-art performance reported at the PDR meeting of the (few) existing SIS mixers operating in the Band 10 frequency range (787-950 GHz) and the additional ALMA requirement for series production, a trade-off between sensitivity and RF bandwidth may become necessary. Some panel members pointed out that not even the best single mixers existing today (HIFI and CHAMP+) would meet the ALMA Band 10 noise specification. The review board recommends that a discussion be started with the ALMA project and science IPT about the realizability of the ALMA Band 10 noise specifications and possible optimizations/tradeoffs on sensitivity and RF bandwidth. NAOJ in conjunction with NICT, ASIAA and the science IPT is asked to create *Junction Selection Criteria* which will allow the different junction technologies to be evaluated for RF performance as well as manufacturability.

We should not be surprised that it is proving difficult to meet the requirements – Band 10 is the first ALMA band above the gap frequency of Niobium. (This means, amongst other things, that the photons have sufficient energy to break the Cooper pairs and therefore Niobium become lossy.) This is discussed in more detail in further excerpts from the Review Panel’s report given below. Also attached for reference is the case for Band 10 that was produced by ASAC in October 2001.

As I see it the key questions are:

1) Is it more important to have reasonable performance over the whole band or very good performance over some restricted part of the band?
2) If the latter, then which is the most important part of the band?
3) What is the minimum noise performance that would be acceptable to make the effort and expense of building these receivers worthwhile?

Obviously the last question is the difficult one and we may not be able to get very far with that right now. It is worth noting that for the Band 9 the noise temperature requirement is for 175K over 80% of the band and I believe that the cartridges delivered so far have done substantially better than that.

REH   21st May 2008

From the Band 10 PDR:

SIS junctions. Although progress has been rapid and impressive since the start of the Band 10 development at NAOJ, the fabricated SIS junctions do not yet enable mixers which meet ALMA specifications over the full band. Given the special difficulty of Band 10 and the few good results worldwide in this frequency range, much attention and further development is required to achieve the best mixer performance. The Review Panel strongly recommends to assess the status of the SIS junction development in an expert meeting between PDR and CDR with the goal to have the possibility for corrective actions on the chosen development strategy. This assessment could e.g. be scheduled in the second quarter of 2009.

Context: The Review Panel recognized the special challenge of the ALMA Band 10 development which is the most difficult band of the ALMA project. The reason is basically twofold:

(1)Being the highest frequency band of ALMA, the optical, mechanical, manufacturing and assembly tolerances are the most demanding of any band, and

(2) established (but still challenging) Niobium SIS junction technology as used for all other ALMA bands is not suitable to achieve the required sensitivity and cannot be used for Band 10. SIS junctions using Niobium as superconductor show increased losses (and hence reduced performance) above ~700 GHz corresponding to the superconductor energy gap of this material.

Band 10 requires the use of different SIS junctions, and more than one development approach has been followed by the Band 10 team. It is generally recognized that these different junction technologies are not as mature as those used for lower frequency bands and present a significant challenge.

There are only a few examples of SIS mixers operating worldwide in the frequency range of Band 10 (787 GHz to 950 GHz) or above which can serve as reference points for the achieved state-of-the-art. Among these are the mixers for the Herschel-HIFI space instrument and the CHAMP+ high-frequency array at the APEX telescope which both cover a very similar frequency band. The Review Panel discussed sensitivity comparisons between these existing mixers and the ALMA Band 10 noise specifications. It turns out that the CHAMP+ mixers would not meet the ALMA specification, whereas at first sight the HIFI mixers would. However, the usually quoted noise performance for the HIFI mixers is for the *mixers only* while the ALMA specification is for the whole cartridge, and the HIFI mixers operate at a physical temperature of 2 K while the Band 10 mixers will operate at 4 K. Putting the HIFI mixers into the ALMA environment, i.e. at an operating temperature of 4 K and using the Band 10 dewar window, IR filter, cartridge optics, and IF amplifiers, it is very doubtful whether the (excellent) HIFI mixers could meet the ALMA spec. It is noted here that some Review Panel members with relevant experience voiced the opinion that the ALMA Band 10 noise specification may be too ambitious and would not even be met by the best existing (hand picked) mixers today, let alone the added difficulty to produce more than hundred state-of-the-art mixers for ALMA.

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4.5.3 SIS Junctions

4.5.3.1 Introduction

Mixer chip fabrication is one of the three primary challenges the band 10 effort is facing. The review board acknowledges that the mixer noise temperature and bandwidth goals for this band are very challenging.

First, the noise temperatures goals were partially based on extrapolation from lower frequency ALMA bands as well as results from HIFI at a physical bath temperature of 2 K, while the band 10 mixers must operate at a physical temperature of 4 K. The ALMA Band 10 *cartridge noise specification* is 230 K over 80% of the band, and 344 K for the rest. However, taking into account the contributions from optics, windows, IR filters, and IF amplifiers, the *mixer noise specification* for band 10 turns out to be only 165 K (2 hν/k_B) over 80% of the band. This would be state-of-the-art even at a lower frequency.

Second, the fixed tuned bandwidth required (787-950 GHz) is large as compared to most operational instruments. Lastly, unlike the other ALMA bands, an all Nb solution is not possible because the band is above the Nb gap frequency (≈700 GHz). It is acknowledged that substantial progress has been achieved over the last year, and that the mixer noise goal has been achieved over a narrow bandwidth (see Fig. 1).

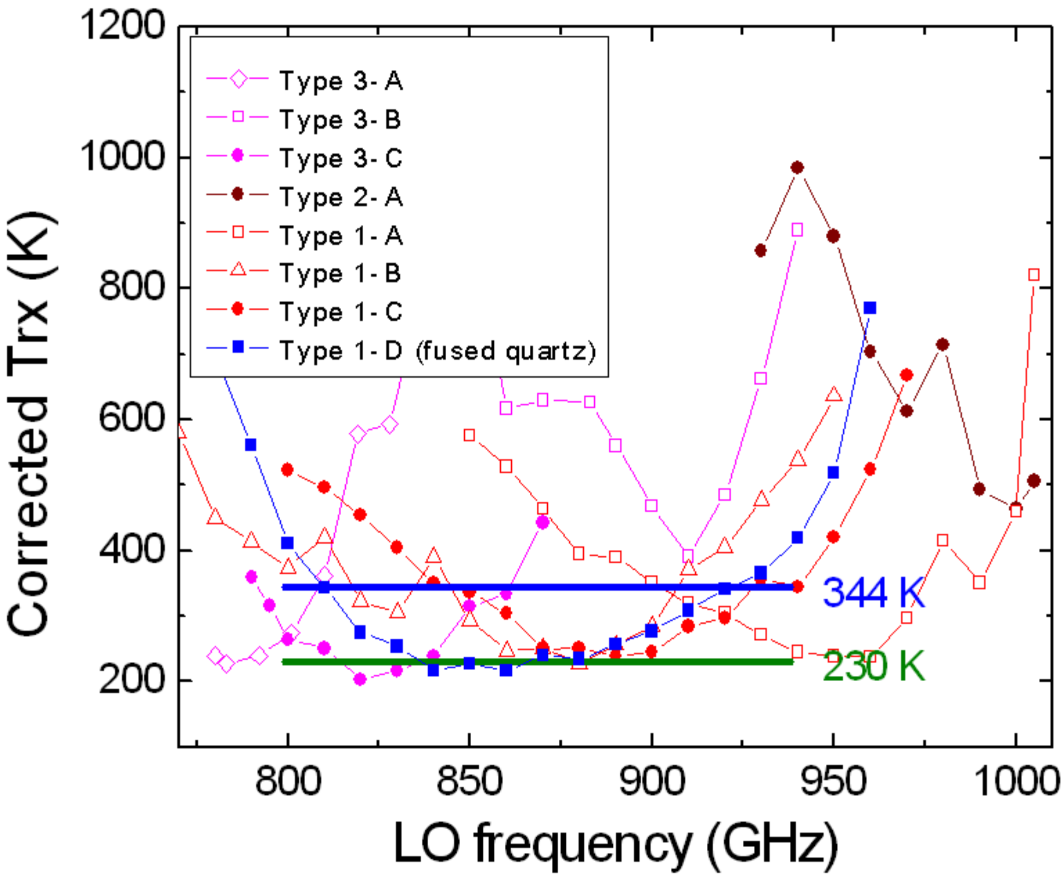

Figure 1 – ALMA Band 10 mixer noise temperatures for different SIS junction technologies and batches (corrected for beam splitter and vacuum window). The ALMA cartridge noise specification is 230 K (DSB) over 80% of the band, and 344 K for the rest.

4.5.3.2 Junction Fabrication

Two distinct junction technologies at three junction labs (NAOJ, NICT, ASIAA) are being pursued for band 10. The first approach uses a hybrid structure of a Nb tunnel junctions and a Nb(TiN)N—Al micro strip tuning circuit. This approach is similar to that used in HIFI bands 3 and 4. The second approach uses NbN tunnel junctions in an all Nb(Ti)N microstrip tuning circuit. Because the all Nb(Ti)N tuning circuit has very low losses over the entire band, this approach has the potential for very low mixer noise as demonstrated by the current results.

However, because the specific capacitance of these junctions is much higher than all-Nb junctions, significantly higher critical current densities are required. It is not clear if low leakage tunnel junctions can be fabricated at these higher current densities. Additionally, the manufacture of all Nb(Ti)N junctions and circuits will likely be more difficult to control. As a result, the hybrid mixers should be viewed as a baseline, and the all Nb(Ti)N mixers as the high risk, high reward approach. A down-selection to one technology may be required at the assessment milestone in one year's time.

Nb junctions with hybrid micro strip

NAOJ and ASIAA are fabricating all Nb junctions with hybrid Nb(Ti)N—Al micro strip line tuning circuits. The challenge for this approach is to fabricate high current density junctions on top of a Nb(Ti)N ground plane. There is some disagreement on the current density required by the 787-950 GHz RF band; at a minimum, high-quality 10 kA/cm^2 junctions are required. It should be noted that higher current density junctions will lower the Q of the tuning circuit, which will result in lower loss in the tuning circuit. And a higher current density will yield a wider RF bandwidth, thus reducing the manufacturing tolerance on the mixer tuning circuit. To achieve high quality tunnel junctions for J_c>10 kA/cm^2, it is necessary to use AlN_x tunnel barriers. NAOJ is currently installing an ICP nitridation source to pursue this option.

The Board strongly recommends this effort be given a high priority.

Because the nitridation must be done in the load lock, the Board *recommends that a nitrogen purged glove box be installed on the load lock to help control the background water vapor in the load lock chamber.* The goal for this effort should be a demonstration of a $Nb/AlN_x/Nb$ mixer at >15 kA/cm^2 by the time of the one year assessment milestone. The ASIAA is achieving the nitrogen plasma by RF biasing the substrate in nitrogen background. This method has not been demonstrated to be reproducible. If possible, the ASIAA should install an ICP or parallel plate nitridation source in their vacuum system. If this is not possible, it may be most constructive for the ASIAA to focus on high Jc $Nb/AlO_x/Nb$ tunnel junctions.

Repeatable demonstration and characterization of a $\geq$ 10 kA/cm^2 hybrid junction should be a priority for the next six to twelve months. The RF performance of such a mixer would allow the NAOJ and the science IPT to determine appropriate system sensitivity goals for band 10.

All NbN mixers

All NbN mixers have the potential to achieve lower mixer noise than hybrid junctions, because the micro strip line tuning circuit can have very low loss. Results from NICT show the lowest mixer noise temperatures thus far, and have met the receiver noise goals over a narrow bandwidth. Unfortunately, because of the low current density of the junctions, the 3 dB bandwidth of this mixer was approximately 50 GHz. Again, there is some disagreement on the critical current density needed for these mixers. However, at a minimum, high-quality, 40 kA/cm^2, all NbN tunnel junctions are needed. In addition, this fabrication process is likely to be more difficult to control, and an extra effort to document and control the reproducibility will be needed. Lastly, the storage lifetime of thinned MgO mixer chips should receive additional documentation.

4.5.3.3 Manufacturability and Reliability

One unique challenge presented by ALMA is the large number of mixers for each band (>100). The number of mixers means that individual pre-selection of the mixer chips based on RF performance (the scheme employed for HIFI and other high-frequency mixers) would result in a very high testing effort which may easily become prohibitive. Rather the large majority of mixers that pass a DC-screening-check need to perform within the band specifications. Additionally the number of design variations on each wafer will have to be kept to a minimum to yield a sufficient number of working mixers. The RF bandwidth of these mixers must also match the design band of 787-950 GHz. These constraints imply that the mixer fabrication process must have high yield and excellent reproducibility. The first step in gauging the manufacturability of the current junction processes is to consistently document and track fabrication parameters for all mixer lots. A partial list of parameters to track are the junction J_c., ground plane and wiring layer properties (resistivity, and T_c), junction size and variation from the design size, subgap resistance, device yield, dimension control on the wiring layer, layer-to-layer registration error, and mixer performance including bandwidth, noise temperature, response across the IF band. In particular the mixer properties which are tracked should reflect the *junction selection criteria* (see below), which will have to be agreed upon in conjunction with the Science IPT. Good documentation will allow NAOJ to judge how reproducible each junction process is, and it will allow the individual groups to determine how they can improve their junction processes.

In addition, high quality documentation will make it much easier to transfer the junction processing to NAOJ for the maintenance stage of the project. On the topic of transfer of SIS junction technology from other labs to NAOJ, the Board recommends to build up a stock pile of suitable SIS junctions before such a transfer is done (AI-20).

4.5.3.4 Junction Selection Criteria

In order to be able to build the large number of Band 10 mixers required for ALMA, clear criteria for SIS junction selection are needed. Given the state-of-the-art, a trade-off between sensitivity and RF bandwidth may become necessary. The science IPT needs to be involved in discussions about these trade-offs. The Review Board is convinced that selection criteria for the mixer chips must be established, so that the different junction technologies and fabrication lots can be evaluated. *Selection criteria should be set by the NAOJ in consultation with the Science IPT, which accurately reflect the scientific and engineering requirements (including manufacturability) of the band 10 cartridge.*

VI. ALMA Band 10: 767–950 GHz

Band 10 is the highest frequency observing band of ALMA, thus providing the highest angular resolution for a given configuration. It offers the following unique science opportunities.

1. Excited [C I] fine structure line

The second $^3P_2 -^3 P_1$ fine structure transition of neutral carbon lies at 809 GHz. This line, along with the lower-lying [C I] $^3P_1 -^3 P_0$ 492 GHz line in Band 8, traces the transition layers between the atomic and molecular gas. Therefore, the [C I] observations provide essential information on cloud structure and evolution in our Galaxy (see Band 8 science case). Whereas the 492 GHz line traces the total [C I] column density, the 809 GHz line is much more sensitive to the gas density and temperature (see Fig. 9). With the high spatial resolution and high sensitivity of ALMA, the detailed distribution of the two [C I] lines can be explored in different types of external galaxies to study cloud formation and destruction on galaxy scales (see also Fig. 8). This is an entirely new field of astrophysics, which can be opened with ALMA for the first time.

2. Red-shifted [C II] emission

Observations of red-shifted atomic lines such as the [C II] 158 μm and [N II] 205 μm lines from distant galaxies are other important targets for Band 10. In particular, Band 10 enables observations of the [C II] emission from galaxies with $z = 1.0 - 1.4$. This redshift range is of interest because of the strong galaxy evolution near $z \sim 1$ (see also case for CO at $z \approx 1$ for Band 4). These [C II] properties and the CO/[C II] ratios at intermediate redshifts $z \sim 1$ must be compared with those at much larger z to be observed in Bands 3–9 corresponding to $z = 2 - 20$.

3. High excitation lines of fundamental molecules

Another important aspect of Band 10 is the rich variety of high excitation lines of fundamental molecules such as HCN J=9–8, 10–9 and HCO$^+$ J=9–8, 10–9. For instance, the J=10–9 line of HCN has an upper state energy of 230 K, and probes densities of at least 10^8 cm^{-3}. Not only lines in the ground state, but also in excited vibrational states with energies >1000 K can be detected and imaged with the ALMA sensitivity (see Fig. 10). These lines are therefore unique probes of the hottest and densest parts of star-forming regions, protoplanetary disks, and galactic nuclei. Note that the HCN and HCO$^+$ 9–8 lines are the first accessible ones after the J=4–3 lines in Band 7, because the J=5–4 to 8–7 lines are significantly blocked by the Earth's atmosphere. Maser emission in the vibrationally excited HCN J= 9 - 8 line has also recently been observed toward late-type stars (Schilke et al. 2000, ApJ 528, L37). High spatial resolution ALMA observations of this line will give new insight into the energetic phenomena associated with the mass loss processes of late-type stars. Finally, the CO J=7–6 line occurs at 807 GHz, tracing warm (>200 K) and dense gas in both local and more distant objects. This line will serve as a powerful tool to investigate the central regions of starburst galaxies and AGN.

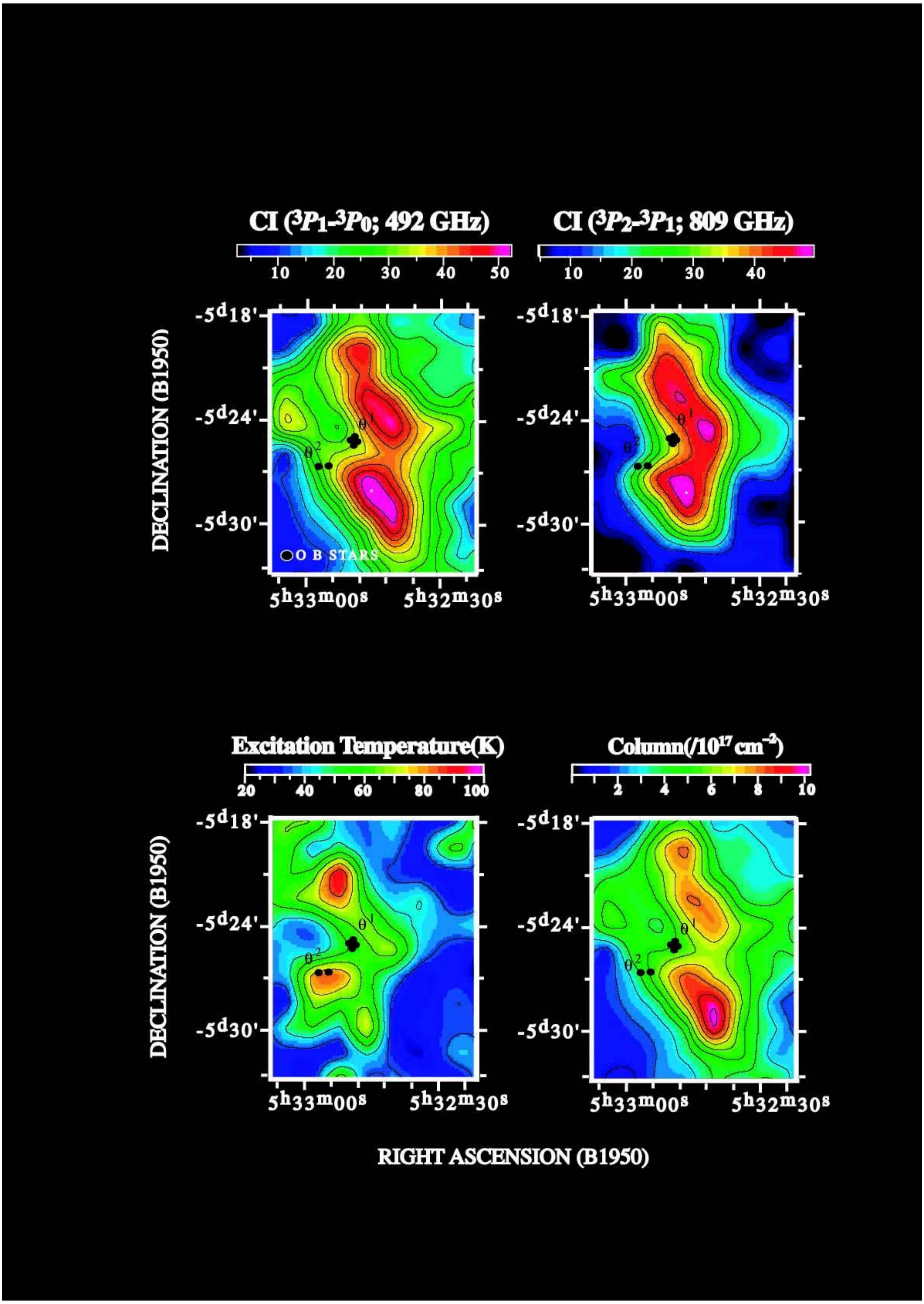

Figure 9. Distributions of the [C I] $^3P_1 - ^3P_0$ (492 GHz) and $^3P_2 - ^3P_1$ (809 GHz) emission around Orion KL observed with the Mount Fuji submillimeter-wave telescope. The 492 GHz line mostly traces the column density, whereas the 809 GHz line is sensitive to the gas temperature (Kuboi et al. 2001, in preparation).

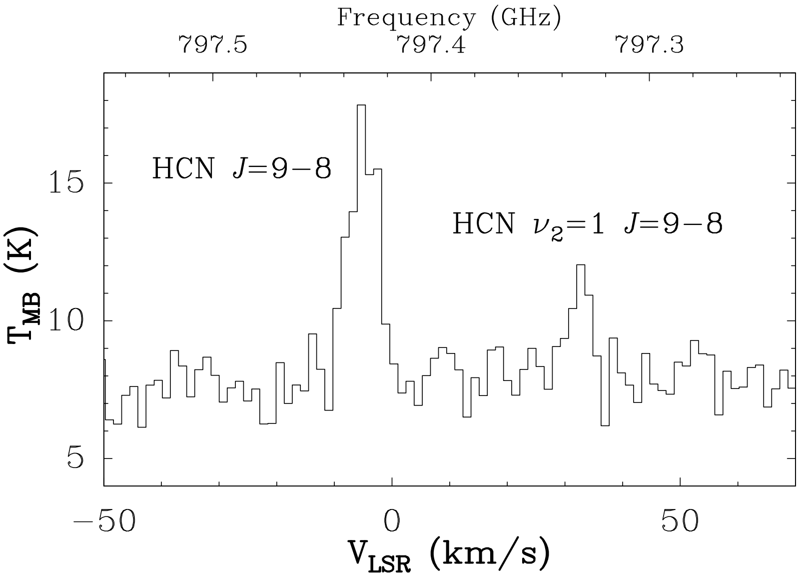

Figure 10. The HCN J=9–8 line together with its vibrational satellite observed toward the massive protostar GL 2591. These highly-excited lines probe the conditions of the 'hot core' in the inner few hundred AU near the young star, and can be used to trace the its evolution (Boonman et al. 2001, ApJ 553, L63).

4. Dust continuum emission

Continuum measurements at Band 10 will provide flux information at the highest frequency of ALMA, which will be important for accurate determination of the spectral energy distribution (SED) of objects like protostellar cores, protoplanetary disks, and active galactic nuclei (see also Fig. 6). For example, for protoplanetary disks multi-band photometry is essential to derive both the optical depth and the grain properties, which may give a clue to understanding of grain growth leading to planet formation. Furthermore, the highest angular resolution of ALMA can be achieved with a combination of Band 10 and the longest baselines, which is needed for imaging protoplanetary disks and identifying gaps created by (proto-)planets on scales of 1 AU in the nearest star-forming regions. This high angular resolution at the highest submillimeter frequencies is also important for bridging the gap with (future) ground- and space-based mid-infrared observatories. For distant galaxies, the Band 10 observations can be used together with far-infrared data from SIRTF, ASTRO-F and/or Herschel to determine their bolometric luminosity and photometric redshifts. For $z \approx 5$, the continuum flux will peak in Band 10 (see Fig. 6).