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Orion-KL Observations with the Extended Tuning Range of the New SEPIA660 APEX Facility Instrument

Francisco Miguel Montenegro-Montes [1]
Karl Torstensson [1]
Rodrigo Parra [1]
Juan Pablo Pérez-Beaupuits [1]
Lars-Åke Nyman [1]
Claudio Agurto [1]
Francisco Azagra [1]
Mauricio Cárdenas [1]
Edouard González [1]
Felipe MacAuliffe [1]
Paulina Venegas [1]
Carlos De Breuck [1]
Per Bergman [2]
Diah Setia Gunawan [3]
Friedrich Wyrowski [4]
Thomas Stanke [1]
Victor Belitsky [2]
Mathias Fredrixon [2]
Denis Meledin [2]
Michael Olberg [2]
Magnus Strandberg [2]
Erik Sundin [2]
Joost Adema [5]
Jan Barkhof [5]
Andrey Baryshev [5]
Ronald Hesper [5]
Andrey Khudchenko [5]

[1] ESO
[2] Chalmers University of Technology, Onsala Space Observatory (OSO), Sweden
[3] IFA Universidad de Valparaíso, Chile
[4] Max-Planck-Institut für Radiastronomie (MPIfR), Bonn, Germany
[5] NOVA Submillimetre Instrumentation Group, Kapteyn Astronomical Institute, University of Groningen, the Netherlands

During Science Verification of the new SEPIA660 facility receiver at APEX, we carried out a shallow line survey of the archetypal Kleinmann-Low Nebula in the Orion star forming region (Orion-KL). These observations cover the tuning range towards the band edges, which has recently been extended beyond ALMA Band 9 specifications. At these frequencies, atmospheric transmission is very low but still sufficient to detect bright lines in Orion-KL. We present the collected spectra and compare with surveys from the literature, demonstrating the capabilities of the instrument.

High frequency submillimetre observations

Submillimetre radiation from space is severely absorbed by water vapour molecules in the Earth's atmosphere. This is why ground-based submillimetre astronomy is exclusively conducted at high and extremely dry places in the world, where the integrated column of precipitable water vapour (PWV) is itself submillimetric. The Chajnantor plateau over the Chilean Andes in Chile Is one of the most outstanding sites available and is where the Atacama Pathfinder Experiment (APEX)[a,1] has been successfully operating for more than a decade, joined more recently by the Atacama Large Millimeter/submillimeter Array (ALMA).

The state-of-the-art instrumentation at these observatories is designed to take advantage of several well-defined spectral windows in which atmospheric transmission is high (see Figure 1), allowing the detection of molecular and atomic transitions to high redshifts, including CO, HCN, HCO+, [C II], [O I]. It is particularly challenging to detect interstellar water, as extremely dry atmospheric conditions are required. Instrumentation groups therefore have to meet the challenge of producing sensitive detectors and spectrometers with large bandwidths in order to exploit premium weather conditions, thus facilitating the study of objects at these wavelengths.

New facility instrumentation at APEX

SEPIA is a multi-receiver instrument (Belitsky et al., 2018) developed by the Group for Advanced Receiver Development (GARD)[2] at Chalmers University in Sweden. It comprises ALMA Bands 5, 7 and 9 (see Figure 1 for their frequency coverage). The SEPIA180 dual-polarisation receiver covers frequencies 159–211 GHz and was installed at APEX in 2015. This is an ESO-OSO Principal Investigator receiver but is offered to APEX user communities of all APEX partners, including Chile. One of its main goals is to observe the 183.3 GHz water transition and high redshift CO lines. The SEPIA345, also

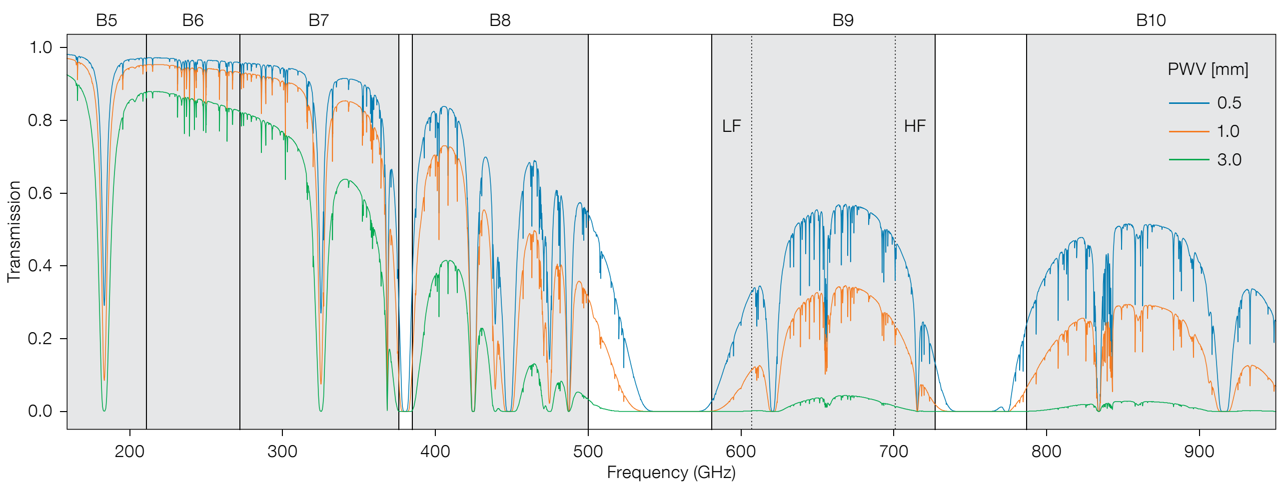

Figure 1. Atmospheric zenith transmission over Chajnantor by Pardo et al. (2001), between 150 and 950 GHz with different amounts of PWV. The spectral coverage of the ALMA bands is indicated along the top axis, as well as the low-frequency and high-frequency ranges of the SEPIA660 band covered in this survey.

developed by the GARD team, will likely be delivered in 2020 as a facility receiver. This is a dual-polarisation, two-sideband (2SB) receiver and will cover the frequency range 275–373 GHz, with a simultaneous bandwidth of 8 GHz. More recently, the SEPIA660 receiver was developed by the NOVA instrumentation group in Groningen. It was installed and commissioned in 2018 and has become the first of the second generation of facility instruments at APEX.

Line ID	f_{sky} [GHz]/SB	Signal band	f_{LO}	Image band
F583L	583.0 LSB	581–585	589.0	593–597
F585L	585.0 LSB	583–587	591.0	595–599
F587L	587.0 LSB	585–589	593.0	597–601
F589L	589.0 LSB	587–591	595.0	599–603
F591L	591.0 LSB	589–593	597.0	601–605
F593L	593.0 LSB	591–595	599.0	603–607
F715U	715.0 USB	713–717	709.0	701–705
F717U	717.0 USB	715–719	711.0	703–707
F719U	719.0 USB	717–721	713.0	705–709
F721U	721.0 USB	719–723	715.0	707–711
F723U	723.0 USB	721–725	717.0	709–713
F725U	725.0 USB	723–727	719.0	709–713

Table 1. List of the 12 spectral setups used in the survey, including the local oscillator frequencies as well as the frequency coverages for both sidebands. All frequencies are in GHz.

In 2020, APEX will also host another facility receiver, the new FaciLity APEX Submillimeter Heterodyne instrument (nFLASH), which is currently being assembled by the Max-Planck-Institut für Radioastronomie (MPIfR) instrument development group in Bonn. This will be a powerful dual-band, dual-polarisation 2SB receiver operating simultaneously over the 230-GHz and 460-GHz frequency windows, also possessing an 8 GHz intermediate frequency bandwidth.

SEPIA660 is an upgraded version of the former SEPIA Band 9 receiver that was integrated at APEX in 2016. The new incarnation was installed and commissioned in the second half of 2018 and comes with important improvements, such as 2SB mixers (see Hesper et al., 2017; 2018) with high sideband rejection (> 20 dB), dual polarisation, and an extended tuning range from 581 to 727 GHz. After technical commissioning a call for Science Verification[3] projects was released inviting programmes that could demonstrate the new capabilities of the receiver. In this context the observations presented here were conceived to verify the performance of the receiver in its extended tuning range.

Orion-KL: a laboratory for astrochemistry

Given the low atmospheric transmission at the edges of the SEPIA660 frequency window, we decided to observe one of the brightest and better-known star-forming regions, Orion-KL (Kleinmann & Low, 1967), where a good number of bright transitions are expected even in a relatively short exposure. Because of the dense line forest in almost all mm and sub-mm windows, Orion-KL is a key reference target used to monitor instrument performance and is observed regularly for cross calibration of science programmes.

Orion-KL is the nearest region in which high-mass stars are being formed and is located 415 pc from the Sun (Menten et al., 2007). Given its vicinity, brightness and chemical complexity, Orion-KL has been used for years as a cosmic laboratory to study the chemistry of high-mass star forming regions. This area contains a good number of embedded young stellar objects that have also been extensively targeted by many ground- and space-based facilities. Examples include deep observations at X-ray wavelengths with Chandra (Getman et al., 2005); in the mid-infrared with Keck (Shuping et al., 2004); in the near infrared with the Son of Isaac (SofI) on the NTT (Muench et al., 2002) and at centimetre wavelengths with the Karl G. Jansky Very Large Array (VLA; Forbrich et al., 2016).

Much earlier VLA observations of this field had already revealed the presence of several compact radio sources, some of which are counterparts of known infrared sources. Source I was found to be associated with SiO maser emission, which is unusual amongst young stellar objects. Extensive follow-up observations have been made of this object, one of the more massive and more luminous in the region (see for example, Hirota, Kim & Honma, 2016, and references therein). Close to Source I is SMA1 and source n. The former is detected at submillimetre wavelengths but not at X-ray or centimetre wavelengths; this is probably due to its being one of the youngest members in the evolving cluster. Source n has a double-peaked morphology and like source I is moving southwards within the cluster (Rodríguez et al., 2017).

In this work, we targeted the coordinates of source I (05:35:14.5-05:22:31.0) and our spatial resolution element is given by the antenna half-power beam width (HPBW), which ranges between 8.6 and 10.7 arcseconds at the observed frequencies. Thus, our beam area covers emission from the complex inner region from which strong molecular outflows in Orion-K are likely to originate and also includes the hot core, source n and SMA1. Other strong sources in the cluster, like the Becklin-Neugebauer object (Becklin & Neugebauer, 1967) or the compact ridge, should be outside the beam coverage.

Several line surveys of this complex have been published in the literature at submillimetre wavelengths, like the Caltech Submillimeter Observatory (CSO) observations published by Schilke et al. (2001) which cover the frequency range 607–725 GHz, partially overlapping with our SEPIA660 observations, or observations from the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel Space Observatory in the framework of the Key Program, Herschel observations of EXtraOrdinary Sources (HEXOS; Crockett et al., 2014).

SEPIA660 observations

The Orion-KL observations were carried out on 13 October 2018 over almost three hours, including pointing, focus, calibrations and the spectral survey. Weather conditions were not ideal for submillimetre observations (PWV was 0.7 mm) but were sufficiently good to

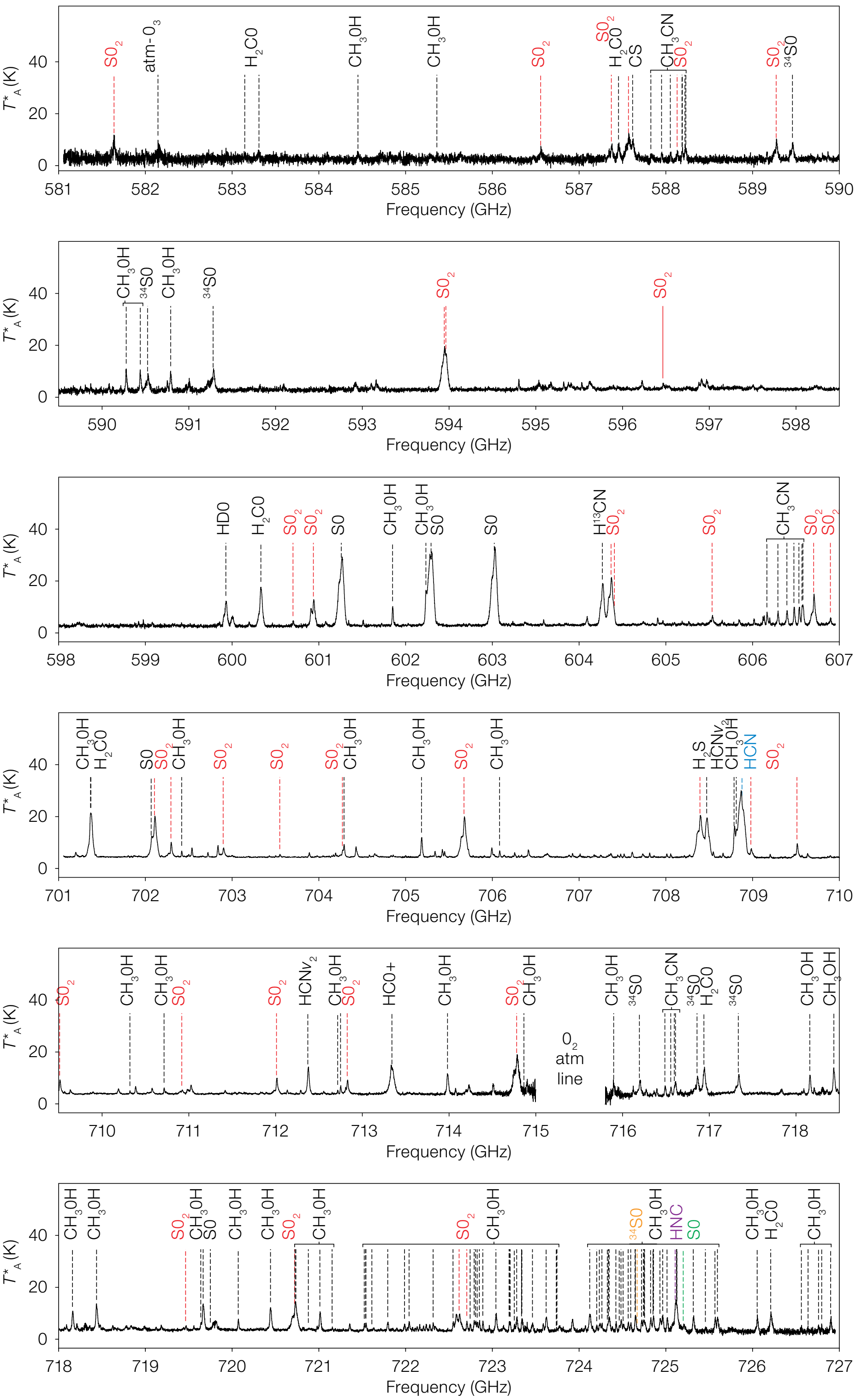

Figure 2. The composite spectrum observed with SEPIA660. The three upper panels correspond to the low-frequency coverage, and the lower ones to the high-frequency window. The most prominent detected lines of selected molecules have been labelled. The portion between 715 and 716 GHz was removed for clarity as it corresponds to severe absorption by atmospheric O_2.

detect the brightest lines in our target. We covered the sky frequencies between 581 and 595 GHz with six spectral setups. Each setup covers 4 GHz in the signal band (and 4 GHz in the image band) and overlaps with the next one by 2 GHz. A similar strategy was followed over the high-frequency range, 713 to 722 GHz (see Table 1 for details).

This approach guarantees homogeneous coverage of all of the low and high frequency ranges (581–607 and 701–727 GHz, respectively), combining the two sidebands. Each tuning was observed for 60 seconds, so each part of the spectrum was covered twice thanks to the frequency overlap between adjacent tunings.

We used the wobbling secondary at a rate of 1.5 Hz to remove the contribution from atmospheric emission. We switched from the target with an azimuthal amplitude of +/– 150 arcseconds in symmetric mode. Since none of the signal or image bands include CO lines, contamination from the off position should not be an issue for the great majority of spectral lines detected.

The datasets were initially calibrated online by the APEX calibrator software, which uses a single opacity correction over each 2.5 GHz segment of the backend. The atmospheric variation in the observed bands requires a finer frequency grid for the opacity calibration correction to effectively remove the atmospheric features. Therefore, we re-calibrated the data channel-wise offline (each channel corresponds to ~ 0.08 MHz). This vectorised method was recently implemented by our online calibrator software and from 2019 onwards has become the default method applied to all APEX data. We compared the online and offline calibration and could verify that the channel-wise approach substantially improves the calibration around the 715.4 GHz molecular oxygen line and a few of the strongest ozone lines. We note, however, that owing to the very low transmission at the lower end of the low-frequency window, the calibration is not able to fully remove the atmospheric ozone line at 582.14 GHz.

In order to produce the final spectra, we removed the outermost 50 MHz at the edges of the band and 100 MHz in

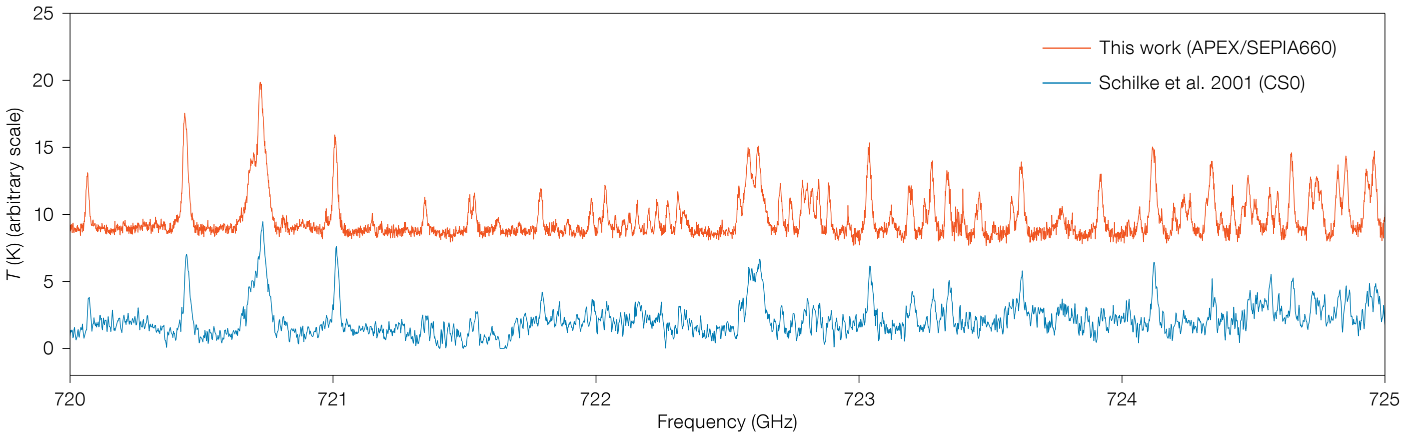

Figure 3. A selected portion of the SEPIA660 spectrum and comparison with a similar dataset by CSO (Schilke et al., 2001). The temperature scale is arbitrary, and an offset between the spectra has been introduced to enable comparison.

the overlap region to avoid the aliasing effects of the spectrometers. Spectra have been resampled from their original spectral resolution to 0.5 km s^{-1} which corresponds to about 1 MHz.

Results and comparison with literature

Figure 2 shows the composite spectrum of the two spectral windows observed. In the low-frequency window (upper three panels), a gradual increase of noise towards lower frequencies results from the increase in atmospheric opacity. For the same reason the higher signal-to-noise corresponds to frequencies between 700 and 710 GHz. More precisely, the noise level is around 1 K root-mean-square in the range 580–585 GHz and ten times lower at 702—704 GHz. There is substantial continuum emission over the band and we have not subtracted any baseline to the spectra shown in Figure 2.

It is beyond the scope of this article to make a complete census and characterisation of molecular transitions; rather we show the most prominent transitions from the species that are known to exist in this region, and compare these with previous existing data in the literature. We have added labels in Figure 2 to the strongest lines detected in our survey: mostly vibrationally excited transitions from methanol (CH_3OH), methyl cyanide (CH_3CN), formaldehyde (H_2CO), sulphur oxides (SO, SO_2, ^{34}SO), deuterated water (HDO), hydrogen cyanide (HCN), isocyanide (HNC) and formylium (HCO^+).

In Figure 3, we compare a portion of our spectrum with the same frequency coverage published by Schilke et al. (2001), taken with the 650-GHz facility dual-sideband (DSB) receiver at the CSO. The CSO observations cover the same region as ours and use a similar beam size (~ 11 arcseconds) so this is an ideal dataset for comparison. Our SEPIA660 spectrum, resampled to 0.5 km s^{-1} perfectly matches the 1 MHz resolution of the CSO data. Since the CSO receiver had DSB mixers, both sidebands are superposed in the final spectrum. In order to separate these, Schilke et al. (2001) had to observe several spectra with different local oscillator frequencies and then apply a maximum entropy deconvolution algorithm. Because SEPIA660 is a 2SB receiver, both sidebands are recorded separately, and no extra deconvolution is needed. In addition, the high sideband rejection ratio ensures minimum contamination from the signal (and noise) between sidebands. Even if the root-mean-square noise per channel is comparable in both APEX and CSO spectra, Figure 3 shows that the baseline of the APEX/SEPIA660 spectrum is much flatter and that weaker lines are detected with higher signal-to-noise ratios.

The part of the spectrum between 725 and 727 GHz that is not covered by the CSO observations from Schilke et al. (2001) is shown in red in Figure 4. This is the last tuning in our frequency range and has only half of the integration time (60 seconds with no overlap). In addition, atmospheric transmission is very low (< 10%), but one can still clearly detect more than 15 lines.

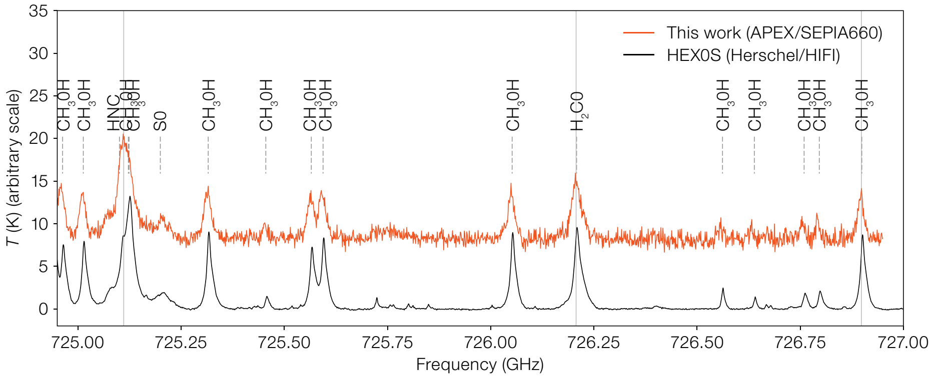

Figure 4. Selected portion of the SEPIA660 spectrum (in red) not covered by the CSO data. Labels have been added to detected lines. The HEXOS spectrum from Herschel/HIFI is also shown for comparison (in black). Note that the temperature scale is arbitrary, and an offset between the spectra has been introduced to enable comparison.

While this portion of the spectrum is not covered by the CSO dataset, it can be compared with the Herschel-HIFI observations from the HEXOS Key Program[b]. To compare our data, we need to keep in mind the different spatial resolutions of Herschel and APEX. At this frequency the Herschel beam size is ~ 30 arcseconds, i.e., an area that is about 11 times bigger than the APEX beam. The Herschel spectrum therefore contains emission from several distinct spatial and velocity components[c], namely the "hot core", the "compact ridge", the "plateau" and the "extended ridge"; all with slightly different line widths and different velocities relative to the local standard of rest, v_{lsr}.

The HIFI spectrum is also shown in Figure 4 (in black). The noise level is much smaller (~ 30 mK) in the Herschel data, but with only 60 seconds integration and a very low atmospheric transmission, SEPIA660 can detect the most prominent features. Long vertical lines mark the peak intensities of three selected line profiles (HNC, H_2CO and (CH_3OH) and different velocity offsets are visible between the two spectra at these transitions, each of them tracing different gas components.

The relatively short observations toward Orion-KL presented here demonstrate the capabilities of SEPIA660 in its extended tuning range, a range not available in the previous incarnation of the instrument, and somewhat beyond the ALMA specifications. Even with the very low atmospheric transmission available in this frequency range, we can detect more than 100 strong lines in this archetypical star-forming region. The good sideband rejection ratio ensures very little contamination between sidebands and makes this instrument ideal for molecular line surveys and for studying the chemistry of the interstellar medium in our Galaxy.

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Links

1 APEX webpage: http://www.apex-telescope.org
2 The GARD team website: https://www.chalmers.se/en/departments/see/research/OSO/gard
3 The Call for SEPIA660 Science Verification: https://www.eso.org/sci/activities/apexsv/sepia/sepia-band-9.html

Notes

a APEX is a collaboration between the MPIfR, OSO, and ESO, with Chile as the host country.
b The HEXOS Orion-KL spectrum was obtained through the NASA Infrared Processing and Analysis Center (IPAC) Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.
c See Crockett et al. (2014) for a detailed description of the different Orion-KL components.

ESO/M. Alexander

APEX is situated on the Chajnantor plain at 5000 metres altitude.