Mid-Infrared High-Dispersion Molecular Spectroscopy using Ge Immersion Grating Spectrograph (IRHS)

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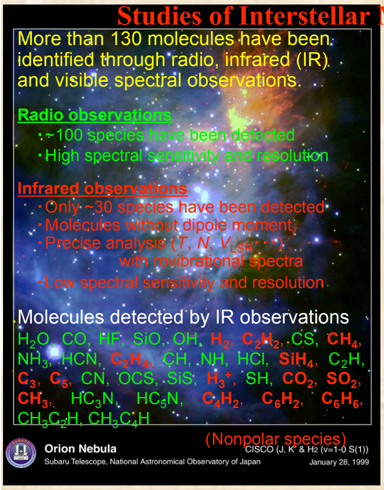
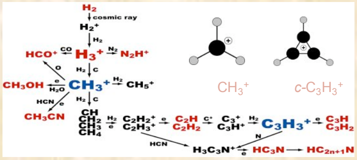
Studies of Interstellar Molecules & Chemistry



The key species without dipole moment have not been detected yet!
e.g. CH_3^+, c-$C_3H_3^+$

→ *Detectable only thru IR observation !!*



The chemistry of dense cloud

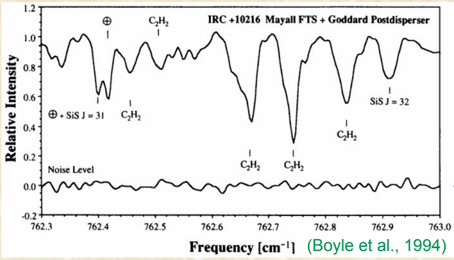
A key species, H_3^+, has been detected using infrared high resolution spectroscopy (T.R.Geballe & T.Oka,1996)

→ *IR observation needed for detailed analysis*

IR High Resolution Observations

Only a few observations were reported so far …

- Orion KL, 4-25 μm, IRTF (3.0 m) & IRSHELL, R = λ/Δλ = 25,000 (Evans et al. 1991)
- IRC+10216, 8-13 μm, Kitt Peak Mayall telescope (4 m) & FTS, R = 100,000 (Keady & Ridgway 1993, Boyle et al. 1994)



(Boyle et al., 1994)

Low sensitivity (S/N = 20, 143 min.): Observable a few objects

Dominant noise source is black body radiation in mid-Infrared region

→ FTS (Fourier-transform spectrometer) is no longer effective

→ *High sensitive and resolution grating spectrometer is needed*

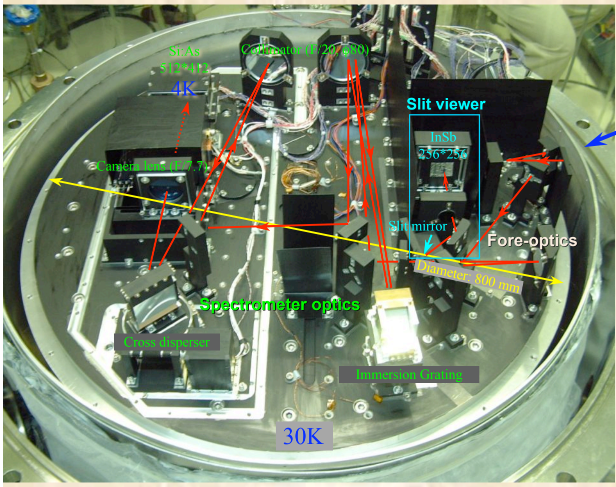
IRHS

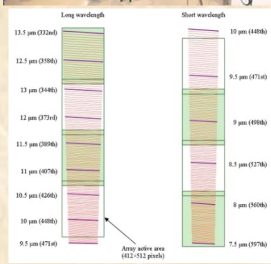
(Mid-InfraRed High dispersion Spectrograph)

- Cryogenic cross-dispersed echelle spectrograph using Ge immersion grating
- High spectral resolution in N-Band (7.5~13.5 μm). Resolving power: R ~ 200,000 @ 10 mm
- For IR Nasmyth focus of 8.2 m Subaru telescope

Optics of Prototype IRHS

To reduce thermal radiation of the instrument, the spectrometer optics is arranged on a cold optical base plate (~30 K) of the cryostat with 80 cm in diameter.



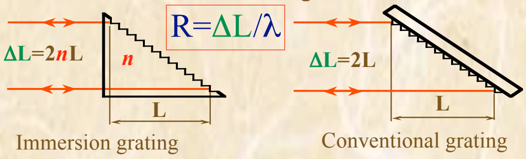


Echelle format

- **Slit width:** 0.612 arcsec (0.488 mm) at R = 50,000
- **Collimator:** Al spherical mirror
  Focal length : 500 mm (F/20)
- **Camera:** Ge and ZnSe lenses
  Focal length : 192.5 mm (F/7.7)
- **Cross Disperser:**
  - Short wavelength (7.5-10 μm)
    Groove constant : 100 grooves/mm
    Blaze angle : 26.7 deg.
  - Long wavelength (10-13.5 μm)
    Groove constant : 61.97 grooves/mm
    Blaze angle : 18.1 deg.

Germanium Immersion Grating

- Directly grooved onto high refractive index material (Refractive index 'n' of Germanium : 4 @ 7-14 μm)
- Increases the resolving power by n-times
- Reduces the size and the weight for the instrument

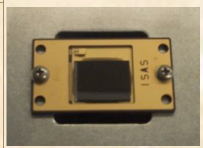


Ge immersion grating: fabricated by " RIKEN" using ELID (ELectrolytic In process Dressing) grinding method.

Focal Plane Array Detector

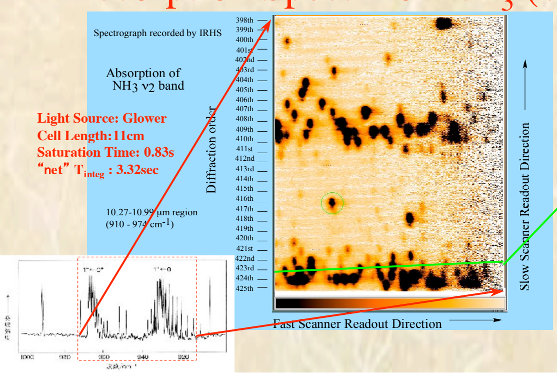
IRHS employed two focal plane array detector manufactured by Raytheon Co. USA.

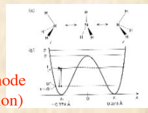
	Si:As IBC	InSb (slit viewer)
Array configuration	512×412 pixels	256×256 pixels
Pixel size	30×30 μm	30×30 μm
Array active area	15.4×12.4 mm	7.7×7.7 mm
Wavelength range	1–28 μm	0.9–5 μm
Operating temperature	4 K	35 K
Well size	~1×10⁵ electrons	~2×10⁵ electrons
Quantum efficiency	> 45 %	> 80 %
Dark current	< 1 electron/s	< 1 electron/s
Readout noise	20 electrons	25 electrons



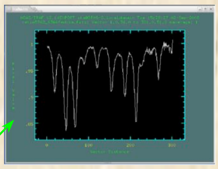
Si:As IBC (Impurity-Band Conductor)

Absorption Spectra of NH_3 (ν_2)



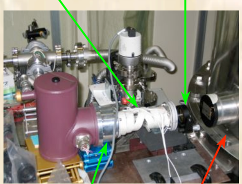


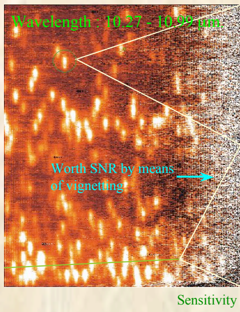
NH_3 ν_2 mode (+ inversion)

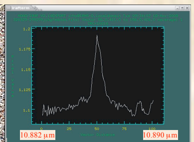


Δν(FWHM) ~8 pixels (0.053 cm⁻¹), ~pressure broadened
N(NH_3)=3 x 10^{18} cm⁻²
High S/N: ~20 for absorbance=1% in 0.166 sec. integration
(cf: ~30 sec. required for the same S/N using FT-IR & MCT detector)

Emission Spectra of NH_3 (ν_2)@300 ºC







N_K=10_{10}(s)-10_{10}(a) : 10.8859 μm (918.621 cm⁻¹)
m= 403rd order (10.877 –10.911 μm).
Δλ(FWHM) ~ 0.000,4 μm (5 pixels).
Resolving power: R~30,000 (focus re-adjustment under way)
Integration : 15 sec

N_{dark}: 150 electron/pix/sec
N_{photon}(210K) : 250 electron/pix/sec

Sensitivity : N_{photon}(Signal) > sqrt {N_{photon}(210K)}

More Advantageous than FTS for Faint Targets, such as Lights from Sky and Discharge Tubes in Laboratory.

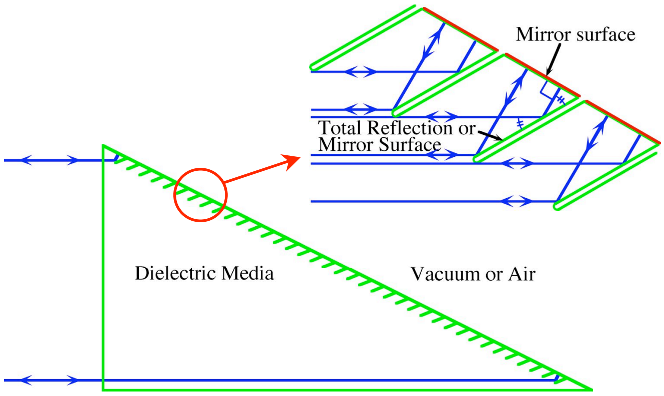
Machine Time for Fabrication of Ge Immersion Grating

Prototype: 30 x 30 x 72 mm
→ about 400 hours

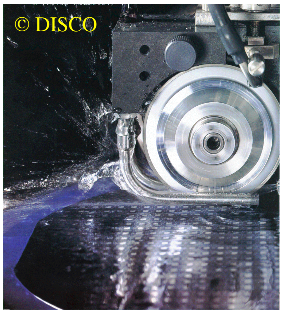
Regular: 120 x 120 x 270 mm
→ several 1000 hours?

Dominant time spent tooling (shaping) for a grinding cup.

Novel Immersion Grating



Fabrication Method for Novel Immersion Grating



- **Smooth surface profile is obtained by a dicing saw.**
- **Tooling of a dicing saw is easy.**

Machine time for regular: 120 x 120 x 270 mm
↓
expect several 100 hours?

[N. Ebizuka et. al., SPIE 6273, 2006]

Scattering Loss of Immersion Gratings

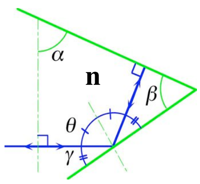
Scattering loss: Ls is given by,

$$Ls = 1\text{-}\exp\{-(4\pi n\,\sigma \cos\theta / \lambda)^2\},$$

where σ is surface roughness in rms.

n = 4.0, σ = 0.05µm, λ = 10µm

θ [deg.]	Ls[%]	θ [deg.]	Ls[%]
0	6.12	45	3.11
15	5.72	60	1.57
30	4.62	75	0.42



Ordinary immersion grating (θ = 0)
Ls = 6.12 %
Novel immersion grating (α = 60, θ = 60)
Ls = $\{1-(1-0.0157)^2\}$ x 100 = 3.12 %

Sensitivity of Prototype IRHS

N_{photon}(Dark) = 150 photons·pixels^{-1}·sec^{-1}

N_{photon}(Background Radiation) :

T_{room} = 290 K : 1,500 photons·pixels^{-1}·sec^{-1}

T_{eff} = 210 K : 250 photons·pixels^{-1}·sec^{-1}

cf. Full-well Capacity (Si:As, 4 K) ~ 200,000 photons·pixels^{-1}

Detectable If N_{photon}(Signal) > $\{N_{photon}(210\ K)\}^{1/2}$

Cryogenic Cooling Allows Us to Extend Integration Time & Enhance SNR.