Research for Formation and Evolution of Massive Star Clusters with SPICA

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The massive star has the considerable influence from its energy in the energy balance and the interstellar matter of galaxies. Moreover, the mass loss from there gives the important effect to the chemical evolution of galaxies and the formation of dust, etc. The understanding is not yet necessarily enough though the evolution of massive stars which has been researched from the theory and the observation. Then, the research of the formation and the evolution of the cluster including the massive stars is advanced by paying attention to the massive star who has short life time such as the OB type star, LBV, YHG, and WR and has a feature profile individually. This is vary effective and important theme not only for individual samples but also to understand in wide-ranging environmental diagnosis theme. We show the plan of a detailed research with SPICA based on previous classification via optical and near-infrared spectroscopy and on the picking up survey of the massive star embedded by interstellar matter.

Features of Massive Stars

Final stage of massive stars
! projenitor of supernovae

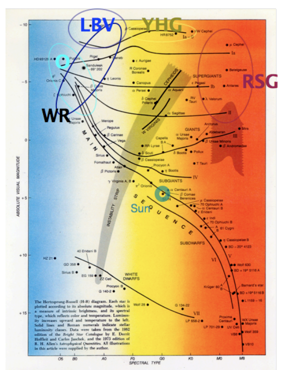
Strong stellar wind
! None hydrogen line
! Feedback to the local interstellar medium

Wide emission lines (He, O, C, N….)

Short lifetime
! few observational sample

WR Wolf-Rayet
LBV Luminous Blue Variable
YHG Yellow Hypergiant
RSG Red Supergiant

WN : Nitrogen sequence
WC : Carbon sequence
WO : Oxygen sequence



Evolution of Wolf-Rayet star

From an evolutionary perspective, the absence of RSGs at high luminosity and presence of H-rich WN stars in young massive clusters suggests the following variation of the Conti scenario in the Milky Ways.

How much mass loss to be SNe ?

$M_{initial}$	MS	post-MS	SN/remnant
>75 M⊙	O3-	→ WNh → LBV → WN → WC/WO →	Ic/BH (GRB?) (fallback or direct)
40-75 M⊙	O5-4	→ LBV → WN → WC/WO →	Ic/BH (GRB?) (fallback or direct)
25-40 M⊙	O7-6	→ LBV → WN / (LBV → RSG → YHG → WN) →	Ib/BH (fallback)
10-25 M⊙	B1-O8	→ LBV → RSG →	IIP,L/NS

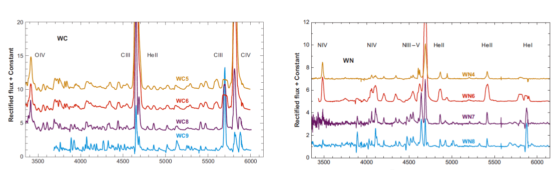
Spectral Feature of Massive Stars

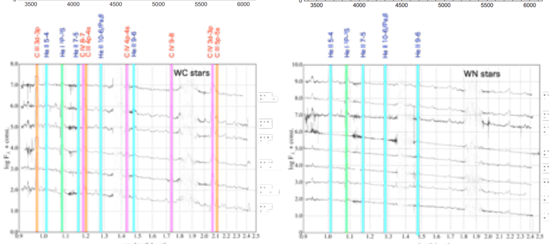
Visual spectral classification of WR stars is based on emission line strengths and line ratios. WN spectral subtypes follow a scheme involving line ratios of N III-V and He I-II, ranging from WN2 to WN5 for early WN (WNE) stars, and WN7 to WN9 for late WN (WNL) stars. WC spectral subtypes depend on the line ratios of C III and C IV lines along with the appearance of O III-V, spanning WC4 to WC9 subtypes, for which WC4–6 stars are early (WCE) and WC7–9 are late (WCL). Rare, O-rich WO stars form an extension of the WCE sequence, exhibiting strong O VI "" 3811–34 emission. The most recent scheme involves WO1 to WO4 subtypes depending on the relative strength of O V-VI and C IV emission lines.

WN type	Nitrogen	Other Criteria	Late/Early
WN9	NIII present, NIV weak or absent	HeI, lower Balmer P Cyg	
WN8	NIII >> NIV, NIII ~ 4686 HeII	HeI, strong P Cyg	WNL
WN7	NIII > NIV, NIII < 4686 HeII	HeI, weak P Cyg	
WN6	NIII ~ NIV, NV present but weak	.....	
WN5	NIII ~ NIV ~ NV	.....	
WN4.5	NIV > NV, NIII weak or absent	.....	WNE
WN4	NIV ~ NV, NIII weak or absent	.....	
WN3	NIV << NV, NIII weak or absent	.....	
WN2.5	NV present, NIV absent	.....	
WN2	NV weak or absent	HeII strong	
WC type	**Carbon Ions**	**Carbon / Oxygen Ions**	
WC9	CIV < CIII	OV weak or absent, CII present	
WC8	CIV < CIII	OV weak or absent, CII not present	
WC7	CIV > CIII	CIII >> OV	
WC6	CIV >> CIII	CIII > OV	
WC5	CIV >> CIII	CIII < OV	
WC4	CIV strong, CIII weak or absent	OV moderate	

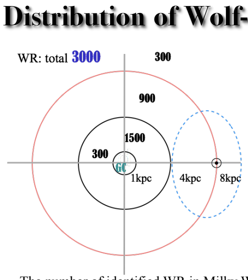
Visible (450-750 nm)		
He I	587.6 706.5	$^3D \rightarrow {^3P}$ $^3S \rightarrow {^3P}$
He II & H	468.6 486.1 541.2 656.0	4 → 3 Hβ 7 → 4 6 → 4 (+Hα)
N III	464.0	
N IV	711.6	
C III	465.0 569.6	3p → 3s 3d → 3p
C IV	466.0 580.5 773.0	6 → 5 3p → 3s 7 → 6
Near-infrared (900-2400 nm)		
He I	1083 2058	$^3P \rightarrow {^3S}$ $^1P \rightarrow {^1S}$
He II & H	1012 1163 1281 2166 2189	5 → 4 7 → 5 10 → 6 (+Paβ) 14 → 8 (+Brγ) 10 → 7
C III	971 1198 2108	3d → 3p 4p → 4s 5p → 5s
C IV	1191 1736 2078	8 → 7 9 → 8 3d → 3p

Emission lines from optical to near-infrared. You can see the difference on each spectrum between WN and WC.





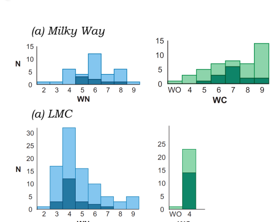
Distribution of Wolf-Rayet star in Milky Way



Distribution of WR in Galaxy (model)
[distribution of Pop I * metallicity]

$$N_{WR}(R) = N_{0,WR}\,\exp\{-(R-R_0)/\sigma_{WR}\}$$
$$N_{0,WR} = 2.2\ \mathrm{kpc}^{-2} \qquad \sigma_{WR} = 2\ \mathrm{kpc}$$
$$\Sigma_{WR}(<R) = \int_0^R N_{WR}(R')\,2\pi R'\,dR'$$
$$\simeq 3000\,\{1-(1+R/2)\,e^{-R/2}\}$$

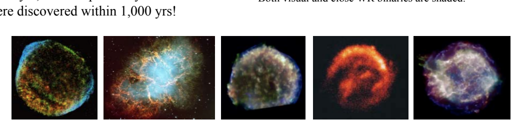
observed region via optical
detection ~ 300 (A_V < 10 mag)



The number of identified WR in Milky Way is ~300. That is only ~10% against model calculation. If lifetime of WR is ~ 105 yrs, ~3 SNe per 100 yrs are detected. For in Milky Way, only 5 Sne were discovered within 1,000 yrs!

Subclass distribution of Milky Way (d<3kpc) and LMC. Both visual and close WR binaries are shaded.

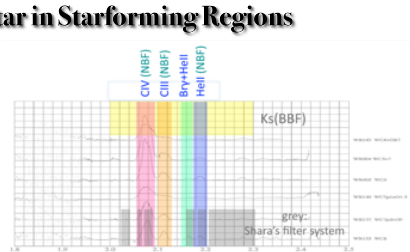
• SN1006 (Ia)	l=328°,	D=2.2 kpc
• SN1054 (II; Crab)	l=185°,	D=2.0 kpc
• SN1572 (Ia; Tycho)	l=120°,	D=2.3 kpc
• SN1604 (Ia; Kepler)	l=5°,	D=6 kpc
• 1680? (II; Cassiopeia A)	l=112°,	D=3.4 kpc



Search for Embedded Massive Star in Starforming Regions

Efficient Tool using NIR

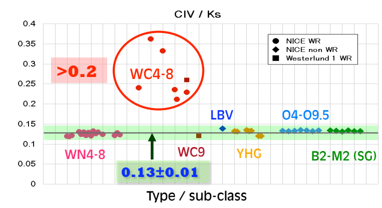
To search for an object embedded in the interstellar medium, usage of long wavelength, that is infrared, becomes efficient tool. In addition, the star can be picked up more efficiently by using a feature emission lines for massive star (WR). The observation carries out by the narrow-band-pass filter which is optimized CIV (2.076um) for WC type WR star and the Ks band filter to pick up early type WC type WR star. Analyzing by "image" base, early WC/WR is picked-up with high efficiency and reliability.



CIV/Ks ratio

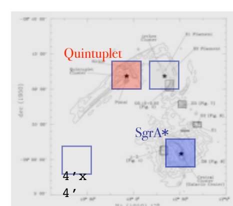
Ratio of CIV/Ks (pass band of each filter are shown in above figure.) Sample are used from archival data which type and subclass are already known.

! <WC8 → CIV/Ks > 0.2
! others → CIV/Ks ~ 0.13

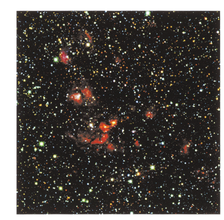


Sample Area

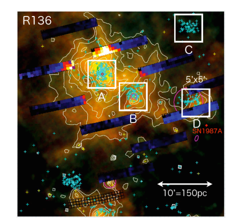
We are making observations by NIR imaging spectroscopy including specialized filter set. The observed regions are 1) high starformation rate, 2) wide range in mass of stars, and 3) active dust-formation environment. Then it is very important region not only massive star formation but also formation and evolution of interstellar medium.



Observaed region for galactic center. Image FOV is 4 arcmin x 4 arcmin (mini TAO/ANIR).



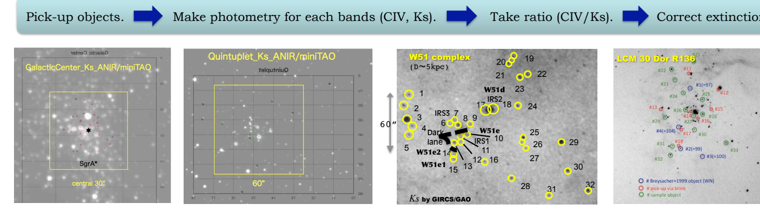
J, *H*, and *K'* composite image of W51 region derived by OASIS/OAO. The image is ~15' across (~30 pc at 7 kpc), covering all area of the H II region complex G49.5-0.4.

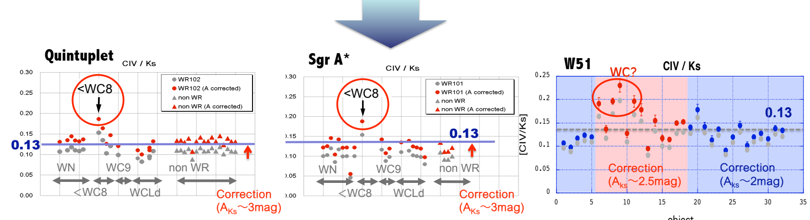


R136 : most active starforming resion of 30 Dor LMC. Slit like positions are observed by AKARI/FIS-FTS ([OIII] image).

Data Analysis

Pick-up objects. → Make photometry for each bands (CIV, Ks). → Take ratio (CIV/Ks). → Correct extinction



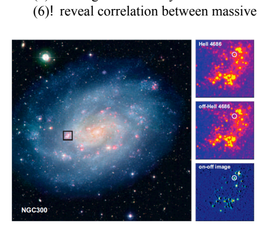


The early WC candidate are detected for each target positions. Besides early WC, the possibility is as follows; (1) extremely blue spectrum, or (2) other emission line(s) are condensed within CIV filter band (ex: HeI). To identify species and its nature, detailed spectroscopy is necessary.

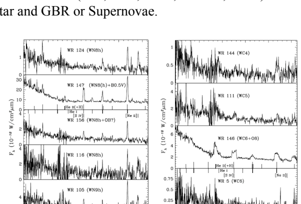
Research for Massive Star with SPICA

Subjects of Massive stars

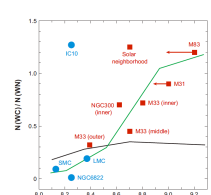
There are many subjects for research of massive star and its environment. SPICA will make an important role to reveal the problems.
(1)! picking-up embedded massive star within interstellar medium.
(2)! increasing sample source especially in extragalactic object.
(3)! exactly determination of effective temperature and subclass using spectrum and ratio of emission lines.
(4)! research for circumstellar dust (dust supply/input by mass loss, destruction & transformation by strong UV photons.
(5)! tracing evolutionally track of various massive star (WR, LBV, YHG, OB star, etc…).
(6)! reveal correlation between massive star and GBR or Supernovae.



Composite ESO Wide Field Imager B,V, R, and Halpha image of NGC300 obtained at the MPG/ESO 2.2m telescope. A number of WR stars showing a He II excess can be seen in the lower right image.



The WN8-9 (left) anf WC4-6 (right) spectra. Equivalent width of HeII 9.7um and Hel + HeII 11.3 um will be indicator to the subclass.



Comparison between th eobserved N(WC)/ N(WN) ration and O content, for nearby spiral (red) and irregular (blue) galaxies, together with evolutionary model.

More high spatial resolution and longer wavelength
! amount of number of embedded WR !
How about for various environment ?

To determine it exactly,
! it is neccesarry high SN spectrum!

How about for other galaxies on different evolutinally stage ?

Advantage of SPICA to research for Massive stars

MIR imaging	Search for embedded object more deeply inside interstellar medium Detailed distribution of dust around massive star
MIR spectroscopy	UIR feature from dust which is origin by massive stars. Fine structure lines by strong UV photon from massive star
Large aperture	Detection of spatially revolved objects (complex such as Galactic center or R136 30Dor) Discovery and Spatial distribution of massive star of extragalaxies
Space telescope	High sensitivity to detect faint sources High spatial resolution

Ion	Wavelength [um]	Ion	Wavelength [um]	Species	Wavelength [um]
O IV	…25.87	Cl II	…14.37, 33.28	He I (blend) + H I (10→7)	… 8.76
Ne II	…12.81	Cl IV	…11.76, 20.38	He I (blend) + H I (13→8)	… 9.39
Ne II	…15.56, 36.02	Cl V	…6.71	He II (13→11)	… 9.70
Ne V	…14.32, 24.28	Ar II	…6.99	He I (1P1→1S0)	… 9.85
Na III	…7.31	Ar III	…8.99, 21.84	He I (blend) + S IV	…10.50
Na IV	…9.04, 21.29	Ar V	…7.90, 13.09	He I (3P0→3S1)	…10.88
Si II	…34.81	K IV	…5.98, 15.39	He I (blend) + He II (brlend)	…11.30
S I	…25.25	Ca V	…11.48	He II (20→15)	…11.72
S III	…18.71, 33.46	Fe I	…24.04, 34.71	He I (blend) + He II (blend)	…12.36
S IV	…10.51	Fe II	…25.99, 35.35	He II (11→10)	…13.12