The GIANO-TNG spectrometer

E. Oliva,[a,b] L. Origlia,[c] C. Baffa,[a] C. Biliotti,[a] P. Bruno,[d] F. D'Amato,[e] C. Del Vecchio,[a] G. Falcini,[a] S. Gennari,[a] F. Ghinassi,[b] E. Giani,[a] M. Gonzalez,[b] F. Leone,[d] M. Lolli,[c] M. Lodi,[b] R. Maiolino,[a] F. Mannucci,[a] G. Marcucci,[f] I. Mochi,[a] P. Montegriffo,[c] E. Rossetti,[c] S. Scuderi,[d] and M. Sozzi[g]

[a] INAF – Osservatorio di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy;
[b] Telescopio Nazionale Galileo, calle A. de Abreu 70/1, E-38700 S.Cruz de La Palma, Spain;
[c] INAF – Osservatorio di Bologna, via Ranzani 1, I-40127 Bologna, Italy;
[d] INAF – Osservatorio di Catania, via S. Sofia 78, I-95123 Catania, Italy;
[e] CNR – Istituto Nazionale di Ottica Applicata L.go. E. Fermi 6, I-50125 Firenze, Italy;
[f] Università di Firenze – Dip. di Astronomia, Largo E. Fermi 5, I-50125 Firenze, Italy;
[g] INAF – Istituto di Radioastronomia, Largo E. Fermi 5, I-50125 Firenze, Italy

ABSTRACT

GIANO is an infrared (0.9–2.5 μm) cross-dispersed echelle spectrometer designed to achieve high resolution, high throughput, wide band coverage and very high stability for accurate radial velocity measurements. It also includes polarimetric capabilities and a low resolution mode with $RS \simeq 400$ and complete 0.75–2.5 μm coverage. This makes it a very versatile, common user instrument which will be permanently mounted and available on the Nasmyth-B foci of the Telescopio Nazionale Galileo (TNG) located at Roque de Los Muchachos Observatory (ORM), La Palma, Spain.

The project is fast-track and relies on well known, relatively standard technologies. It has been recognized as one of the top priority instrumental projects of INAF (the Italian National Institute of Astronomy) and received its first financing for the phase-A study in October 2003. Integration in the laboratory is planned to start before the end of 2006, commissioning at the telescope is foreseen within 2007 and scientific operations in 2008.

One of the most important scientific goals is the search for rocky planets with habitable conditions around low-mass stars. If completed on time, GIANO will be the first and only IR instrument operating worldwide providing the combination of efficiency, spectral resolution, wavelength coverage and stability necessary for this type of research.

With its unique combination of high and low resolution modes, GIANO will also be a very flexible common-user instrument ideal e.g. for quantitative spectroscopy of brown dwarfs, stars and stellar clusters as well as for the determination of the spectral energy distribution of faint/red objects such as high redshift galaxies. The expected limiting magnitudes are such that GIANO will be able to deliver good quality HR spectra of any 2MASS object and LR spectra of any object detected in the UKIDSS large area survey.

Keywords: Ground based infrared instrumentation, infrared spectrometers

1. INTRODUCTION

GIANO is a fast-track and relatively low-cost project for a high resolution near-IR (0.9–2.5 μm) spectrograph with superb spectral stability, very wide spectral coverage and the highest possible efficiency. The instrument will be permanently mounted at a fixed position in the Nasmyth-B focal station of the Italian 3.58m TNG telescope at the ORM observatory in La Palma.

One of primary scientific targets is the search of rocky planets (down to a few Earth masses) around low mass stars by means of accurate (few m/s) radial velocity measurements. Complementary to this highly specific scope, the instrument must also offer top-level observing capabilities of interest for the broad community of solar-system, stellar, galactic and extra-galactic astronomers who greedily access the TNG telescope.

Table 1. Overview of GIANO observing modes

Observing mode[a]	slit-length	RS^b	spectral coverage (μm)
High-res (HR)	6.5"	23,000	0.95 – 2.5[c]
Shifted-High-res (SHR)[d]	6.5"	23,000	0.95 – 2.5[d]
Low-res (LR)	30"	400	0.75 – 2.5

Slit widths: 0.5" (2pix), 0.75" (3pix), 1.0" (4pix), 1.5" (6pix)

[a] All modes can be used with the polarimetric unit
[b] Resolving power for 1" slit
[c] Complete up to 1.7 μm and ≥70% complete in the K band
[d] Accesses the part of the 1.7–2.5 μm spectrum not visible in the HR mode

These apparently contradicting requirements are satisfied by the GIANO instrument which takes its name from the double-faced God of the ancient Romans. Its front face is that of high resolution (R=46,000 with a 2 pixels sampling) cross-dispersed echelle spectrograph delivering a quasi complete 0.95–2.5 μm spectrum in a single shot, while the back face shows a long slit low resolution ($RS \simeq 400$ and $R_{max} \simeq 1000$) spectrometer covering the full 0.75–2.5 μm range with unprecedent throughput, hence ideal for the study of very faint continuum objects. The instrument also includes a polarimetric mode optimized for high resolution observations, but also usable in the low resolution mode.

Detailed descriptions of the various sections of the instrument and of its software and acquisition system are presented in separate contributions to this conference.[1–7] In the following sections we discuss the instrumental capabilities, some of the most relevant scientific drivers and the scheduling of the works foreseen in the next two years.

2. INSTRUMENT CAPABILITIES AND PERFORMANCES

The observing modes of GIANO are summarized in Table 1. The layout of the spectra in the high (HR) and low (LR) resolution modes are visualized in Fig. 1. The spectral range covered in the HR mode is complete up to 1.7 μm and ≃70% complete at 2.45 μm. This compromise follows from the requirement of maximizing the resolving power without excessively decreasing the spectral coverage at the longer wavelengths. Nonetheless, the missing part of the K band can be accessed in the "shifted high resolution mode" (SHR) which is obtained by inserting a thin prism in front of the echelle, i.e. without moving the grating.[5]

On its way to the detector the light from the telescope passes through 11 refractive elements (i.e. 5 warm lenses, 3 cold prisms in double pass), it is reflected 16 times (5 warm mirrors and 7 cold mirrors, 4 of which working in double pass) and, in the HR-mode, it is diffracted by the echelle reflection grating. The overall optical efficiency of the spectrometer and preslit system is therefore expected to be close to 60% in the LR mode and 39% in the HR mode. The GIANO array, an HAWAII 2-PACE delivered in 2005, has a quantum efficiency of 73% in K and 58% in J. Adding a conservative 75% efficiency for the telescope yields a total throughput in the HR mode of 21% and 17% in K and J, respectively, while the figures for the LR mode are 33% (K) and 26% (J). All these values are remarkably high. For the array noise we conservatively adopt a maximum on-chip integration time of 20 minutes and a corresponding total noise of 17 electrons. These numbers are mostly based on our direct experience with the NICS-TNG instrument which employs an HAWAII 1 array.

The resulting limiting magnitudes for representative observing setups are listed in Table 2. It is interesting to note that the numbers for the HR mode are similar to the limiting magnitudes of 2MASS and DENIS, i.e. GIANO can provide high resolution spectra of any object detected by these surveys. Moreover, the sensitivities in the LR mode are well matched to the depth reached by the UKIDSS large area survey.

Table 2. Expected limiting magnitudes for GIANO(1)

HR mode, R=46,000 slit=0.5” seeing=1.0”

Band	S/N=100 in 1hr	S/N=10 in 1hr
J	12.2	15.3
H	11.8	14.9
K	11.2	14.1

HR mode, R=28,000 slit=1.0” seeing=1.0”

Band	S/N=100 in 1hr	S/N=10 in 1hr
J	13.3	16.3
H	13.0	15.9
K	12.1	14.8

LR mode, R=400 slit=1.0” seeing=1.0”

Band	S/N=100 in 1hr	S/N=10 in 1hr
J	16.5	19.1
H	15.6	18.2
K	14.7	17.3

(1)S/N per spectral resolution element.

2.1. Expected performances of GIANO for radial velocity measurements

Compared to the other (and indeed few) high resolution IR spectrographs available or under construction, GIANO is the only instrument offering an almost complete coverage of the spectrum in one shot. In other words, GIANO is the only IR spectrograph with spectral format and coverage comparable to optical instruments currently used for accurate radial velocity measurements.

The photon-noise limit to radial velocity measurements scales with the instrumental resolution, the S/N ratio of the spectrum and the square-root of the effective number of usable lines (N_l). In the specific case of GIANO

$$\sigma(\mathrm{RV}) \simeq 5 \cdot (\mathrm{S/N})^{-1} \cdot (N_l)^{-0.5} \qquad \mathrm{km/s}$$

The cell adopted for GIANO is a combination of halogen hydrates which creates a clean and regular pattern of roto-vibrational absorption lines distributed over most of the J, H and K atmospheric windows (see Fig. 2). Since the spectrum of late-M dwarfs is reach enough to have several stellar features within ∼10 resolution elements of each line of the cell reference spectrum, the effective number of useful lines is practically set by the depth and distribution of the cell absorption features. This has not been measured as yet, but it can be quite accurately predicted[3] because of the simplicity of the molecules and transitions involved. The only important uncertainty is the exact quantity of gas which will be in the cell. As a conservative lower limit one can assume N_l=30, while one can optimistically expect values as large as 200. The corresponding radial velocity accuracies are plotted in Fig. 3 as a function of the stellar magnitude.

3. SCIENTIFIC DRIVERS

The recent development of several IR spectroscopic studies is now facing a shortage of instruments working at high spectral resolution and covering a wide spectral range. GIANO has the unique capability of spanning two orders of magnitude in spectral resolution (from 400 to almost 50,000), to cover most the full near-IR spectral range in one shot and to measure linear and circular polarization. These characteristics will allow to tackle with unprecedented accuracy several important astronomical issues.

In the following some of the scientific cases which will be addressed with GIANO are listed, as gathered by a survey among several Italian groups. It should be noted that some of the scientific drivers discussed in the following cannot be pursued (with the same degree of accuracy) with other existing or planned instruments, even at 8–10m class telescopes.

- *Extra-solar rocky planets.*

  The capability of GIANO to simultaneously measure a huge number of near-IR features at high resolving power will make it the optimal tool in the search for low-mass, rocky planets around cool low-mass stars which are too red for being observed at optical wavelengths. A particularly interesting aspect of this field of research is discussed further in Sect. 3.1.

- *Star-forming regions.*

  By studying the velocity structure of suitable emission lines in star-forming regions it will be possible to obtain fundamental information on accretion/ejection mechanisms in active protostars and on how the activity of low mass young stars evolves from the embedded to the pre-main sequence phase.

- *Cool stellar atmospheres.*

  The unique combination of high spectral resolution, wide spectral coverage, polarimetric capabilities and high sensitivity will allow to derive with unprecedented accuracy the abundances of most atomic and molecular species, the magnetic fields and the mass loss activity in any class of cool star. This information is crucial for our understanding of the stellar physics, evolution and chemical enrichment.

- *Black Holes in obscured AGNs.*

  GIANO will allow to tightly constrain the Black Hole mass in several galactic nuclei which are too obscured by dust to be probed by optical spectrometers. This is in particular the case for obscured AGNs, which are largely the dominant population of active nuclei.

- *IMF in starburst galaxies.*

  By resolving the width of absorption and emission features in dust embedded Super Star Clusters (found in starburst galaxies) it will be possible to tightly constrain their Initial Mass Function (IMF). Henceforth, it will be possible to investigate the dependence of the IMF on the level of activity and metallicity of these systems, which is highly relevant for our understanding of the formation and evolution of stellar systems.

- *Damped Lyα Systems.*

  GIANO will allow to measure the metallicity of high–z Damped Lyα systems by measuring the equivalent width of the associated absorption by various atomic species, which are shifted into the near-IR. This will allow to tightly constrain the metallicity evolution of Damped-Lyα Systems, which is currently poorly known because of the shortage of indicators in the optical at high redshift.

- *Minor Bodies of the Solar System.*

  The wide spectral coverage of GIANO in the low resolution mode will allow to detect various spectral features of minor bodies of the solar system which will allow to unambiguously determine their composition, nature and origin. Obtaining this information on this class of objects will greatly help to understand the formation of the Solar System.

- *Brown Dwarfs.*

  It has been recently shown that a wide, continuous spectral coverage in the near-IR is the optimal tool for the classification of very low mass stars and brown dwarfs. The capabilities of GIANO will not only allow a careful classification of these objects (using the LR mode), but will also allow to study the composition of their atmosphere and their circumstellar activity.

- *Extremely Red Objects.*

  Identifying and understanding the nature of this class of high redshift objects (either dusty starbursts or ellipticals) will greatly benefit of the wide spectral coverage and unique sensitivity of LR mode of GIANO. The spectra will allow to identify spectral breaks typical of the continuum of ellipticals at high redshift. At the same time the moderate spectral resolution will allow to detect emission lines associated to starburst activity. No other instrument would allow for such a complete spectral analysis in this class of objects.

- *Metallicity evolution of starbursts and quasars.*

  GIANO-LR spectra will allow to detect simultaneously, with high sensitivity, several emission lines in high redshift starburst galaxies and quasars.
  The wealth of information and the excellent inter-calibration between the various lines delivered by GIANO will allow to derive the metallicity of these systems with unprecedented accuracy and to obtain a consistent scenario of the metallicity evolution of these high redshift systems.

3.1. Rocky extra-solar planets with habitable conditions

The search of rocky (few Earth-masses) extra-solar planets with habitable conditions around low mass stars is probably the most outstanding program which can be carried out with a specialized IR spectrograph like GIANO. The basic advantage stems from the possibility of observing at infrared wavelengths stars at the bottom of the main sequence which are too cool/red for optical spectrographs.

Let M_* and L_* be the mass and bolometric luminosity of a star hosting a planetary system. The primary condition for a planet to be habitable by a life system similar to that developed on the Earth is that it receives, for several billion years, a quasi-constant flux with intensity similar to the solar constant. This implies that the star must be a main-sequence hydrogen burning object (i.e. not a brown dwarf) and that the planet must lye on a quasi-circular orbit at a distance R_{orb} from the star where it receives a flux similar to that received by the Earth, i.e.

$$R_{orb} = \left(\frac{L_*}{L_\odot}\right)^{0.5} \qquad \text{AU} \tag{1}$$

The corresponding orbital period, P, and velocity, v_{orb}, are

$$P = \left(\frac{M_*}{M_\odot}\right)^{-0.5} \cdot \left(\frac{L_*}{L_\odot}\right)^{0.75} \qquad \text{yr} \tag{2}$$

$$v_{orb} = 29.8 \cdot \left(\frac{M_*}{M_\odot}\right)^{0.5} \cdot \left(\frac{R_{orb}}{1\ \text{AU}}\right)^{-0.5} \qquad \text{km/s} \tag{3}$$

The corresponding modulation on the radial velocity of the star is given by

$$v_{rad} = v_{orb} \cdot \left(\frac{M_{planet}}{M_*}\right) = 0.091 \cdot \left(\frac{M_{planet}}{M_{Earth}}\right) \cdot \left(\frac{M_*}{M_\odot}\right)^{-0.5} \cdot \left(\frac{R_{orb}}{1\ \text{AU}}\right)^{-0.5} \qquad \text{m/s} \tag{4}$$

which combined with Eq. (1) yields

$$v_{rad} = 0.091 \left(\frac{M_{planet}}{M_{Earth}}\right) \cdot \left(\frac{M_*}{M_\odot}\right)^{-0.5} \cdot \left(\frac{L_*}{L_\odot}\right)^{-0.25} \qquad \text{m/s} \tag{5}$$

The luminosity of sub-solar main sequence stars roughly scales with M_*^3. Hence the radial velocity increases as $M_*^{-5/4}$ and approaches 2 m/s for stars close to the hydrogen-burning limit ($\simeq$0.09 $M_\odot$). The corresponding orbital period, which decreases as $M_*^{7/4}$, is about 5 days.

All these considerations are summarized in Fig. 4 which plots, as a function of the stellar mass, the orbital period and induced stellar radial velocity variations for an habitable planet. The steep decrease of P and increase of v_{rad} below 0.09 $M_{\odot}$ marks the transition between normal stars and brown dwarfs.

Given its expected performances (Sect. 2.1) GIANO should therefore allow the detection of planets with a few Earth masses and habitable conditions around the lowest mass hydrogen-burning stars (i.e. late M and early L old dwarfs).

4. GIANO SCHEDULING

The project followed from a 2002 call by INAF (the Italian Institute of Astrophysics) for second generation instruments for the 3.58m Telescopio Nazionale Galileo (TNG) operating at La Palma. GIANO was selected as the top priority project and approved on July 2003. The phase A study terminated in December 2003 with the issuing of a PDR document which was submitted to international Referees. The total cost of instrument was estimated to be close to $1.3{\cdot}10^6$ Euros. Phase B started in 2004 with the financing of 1/3 of the total request. Further financing followed up to about 3/4 of the total (updated on April 2006).

Already in house are the array, the spectrometer optics,[5] part of mechanics and of the preslit elements.[2] The cryostat and cryogenic optical bench (BeTank[4]) are under construction, deliver is expected by autumn 2006. Integration at the INAF-Arcetri laboratories will start immediately after with the alignment and thermal cycling of the aspheric mirrors on the BeTank. The opto-mechanical works on the cryogenic spectrograph is foreseen to last until summer 2007. Parallel to these are the works on the array electronics and acquisition system, which are already well advanced,[1,7] and on the preslit system,[2] which will be mounted and aligned directly at the TNG telescope. Some of the preslit elements will also be tested at the INAF-Catania laboratories.

The transport of the spectrograph to the telescope and the beginning of the commissioning phase are foreseen before the end of 2007, and science operations within 2008.

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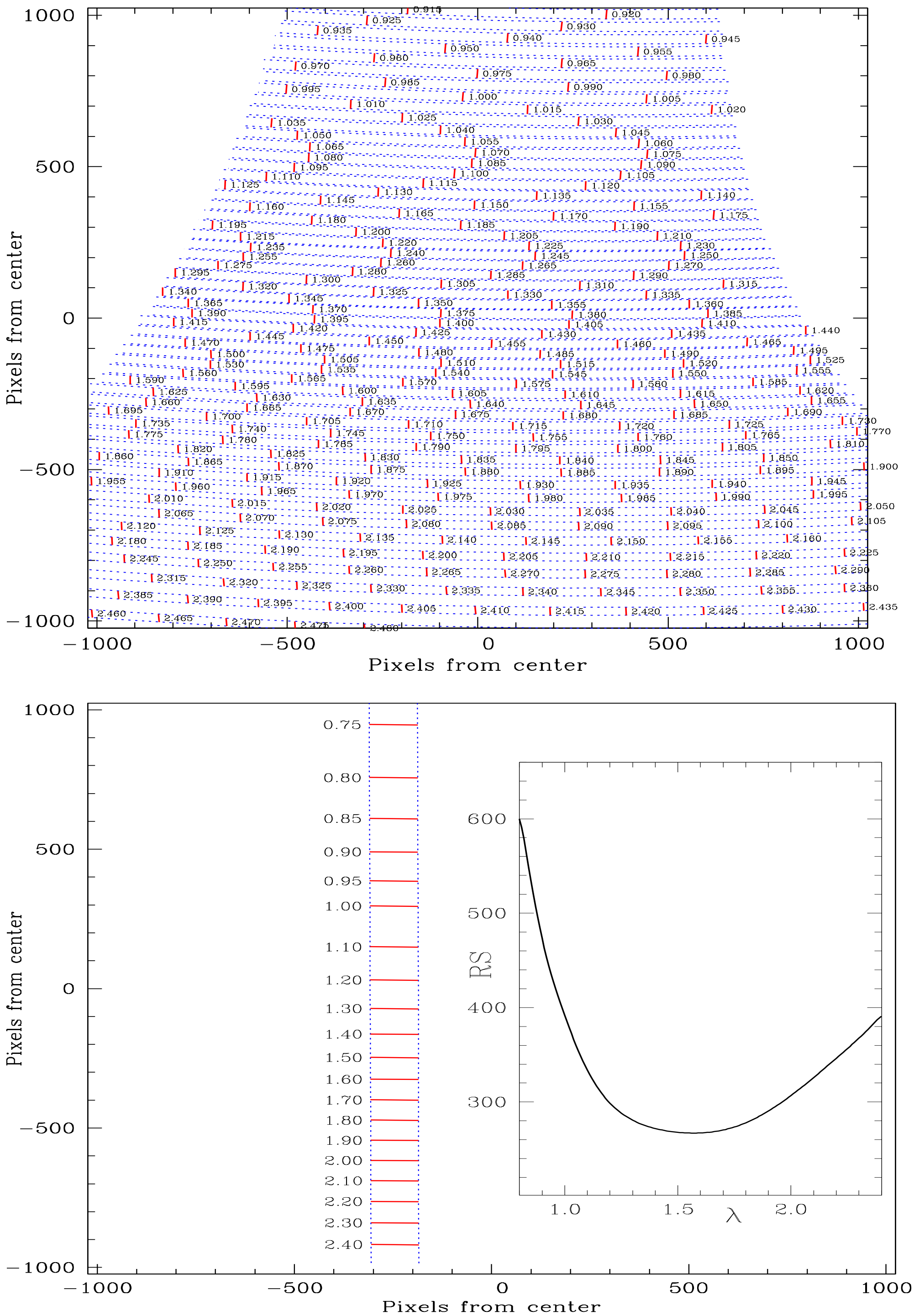

Figure 1. Upper panel: spectral layout of a GIANO spectrum taken in the HR mode. The echellogram includes the orders from 31^{st} ($\lambda_c \simeq 2.5$ μm) to 84^{th} ($\lambda_c \simeq 0.92$ μm). Wavelength coverage is complete up to about 1.7 μm (45^{th} order) and ∼70% complete at 2.5 μm

Lower panel: spectral layout of a GIANO spectrum taken in the LR mode. All wavelengths (numbers on the side of the slit) are in μm. The slit is 30" long and the spectrum is slightly off-centered to allow a simpler 2-quadrants read-out of the array. The inset plot shows the variation of the slit-resolution product (i.e. the resolving power for 1" slit) as a function of wavelength.

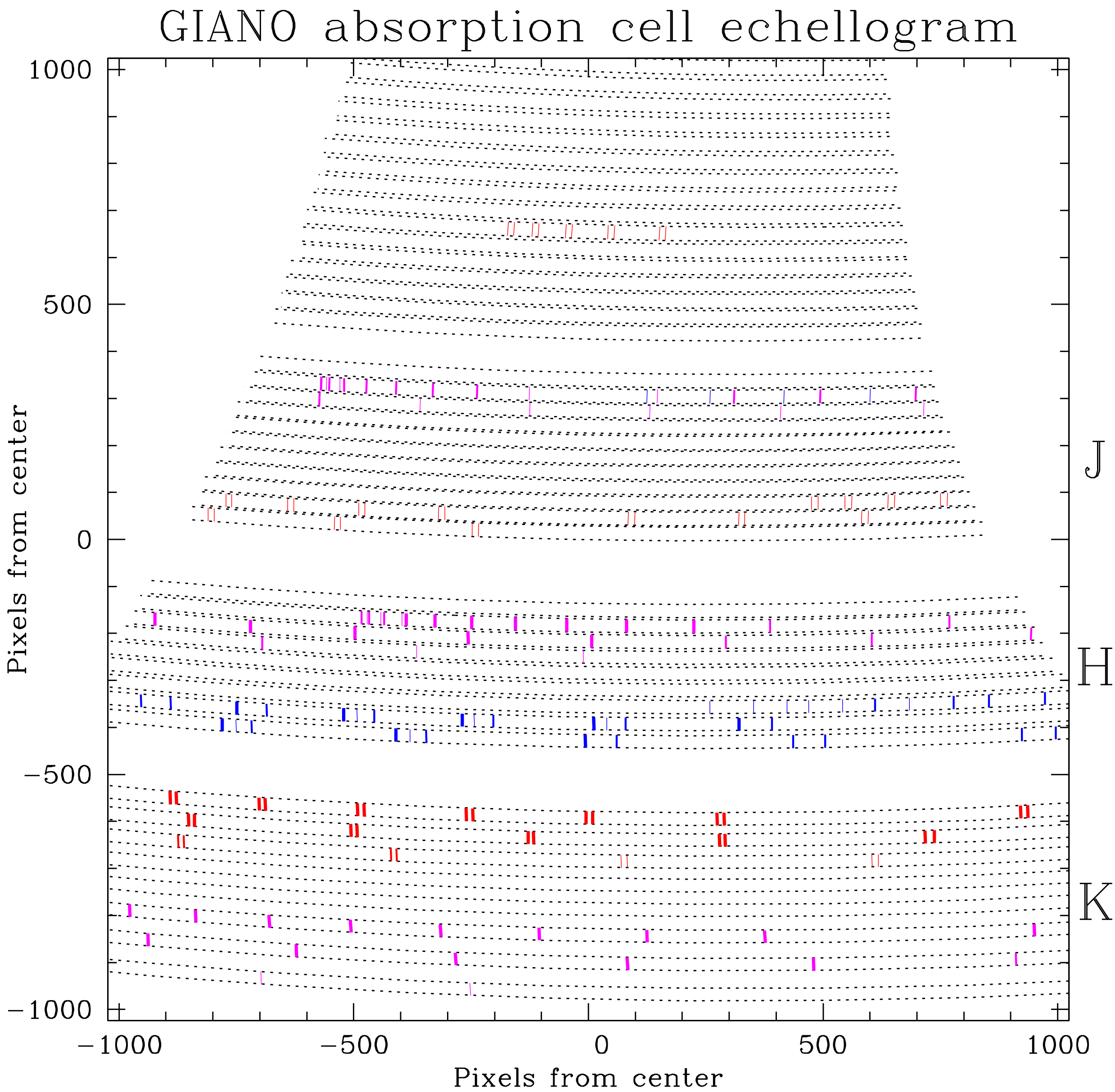

Figure 2. Distribution of the absorption lines produced by the HCl+HBr+HI GIANO-cell[3] on the spectrometer array. The dashed horizontal lines show the position of the usable orders, i.e. those which are not affected by strong telluric absorptions. The lines in the K band are produced by HI (lower group at longer λ's) and HBr (shorter λ's). The lines in the H band are produced by HCl (lower group) and HI (upper group). The lines the the J band are from HBr (lower group) and a mixture of HBr and HCl (upper group). The uppermost lines, at $\lambda \simeq 1.05\ \mu$m, are from HBr.

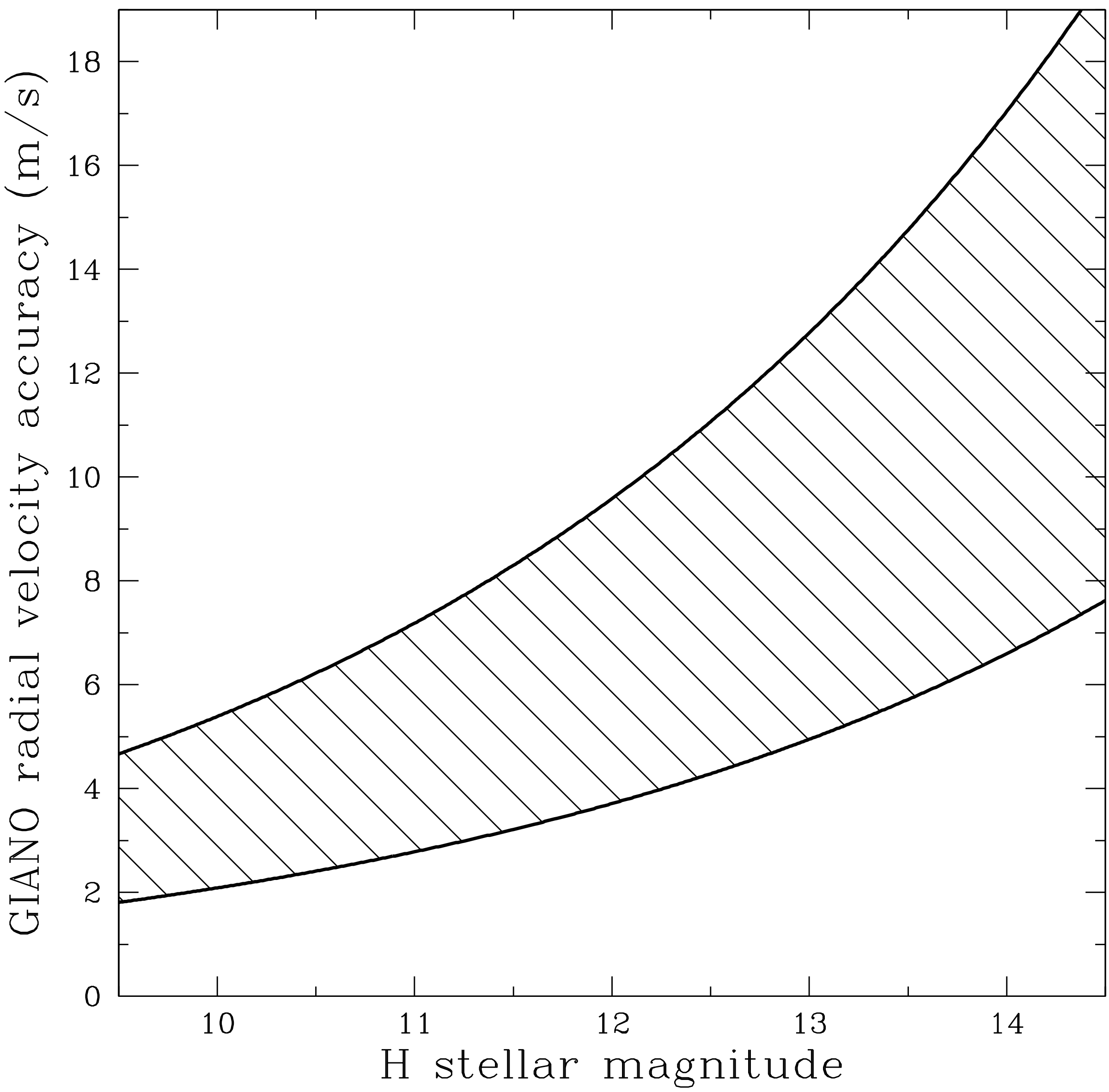

Figure 3. Expected accuracy on radial velocity measurements as a function of stellar magnitude. The curves are the photon noise limit computed for an entrance slit of 0.5", seeing 0.75", total integration time of 1 hour and adopting different assumptions on the effective number of usable lines in the cell reference spectrum (see text for details). The dashed area represents the plausible range of values which should be achievable with GIANO.

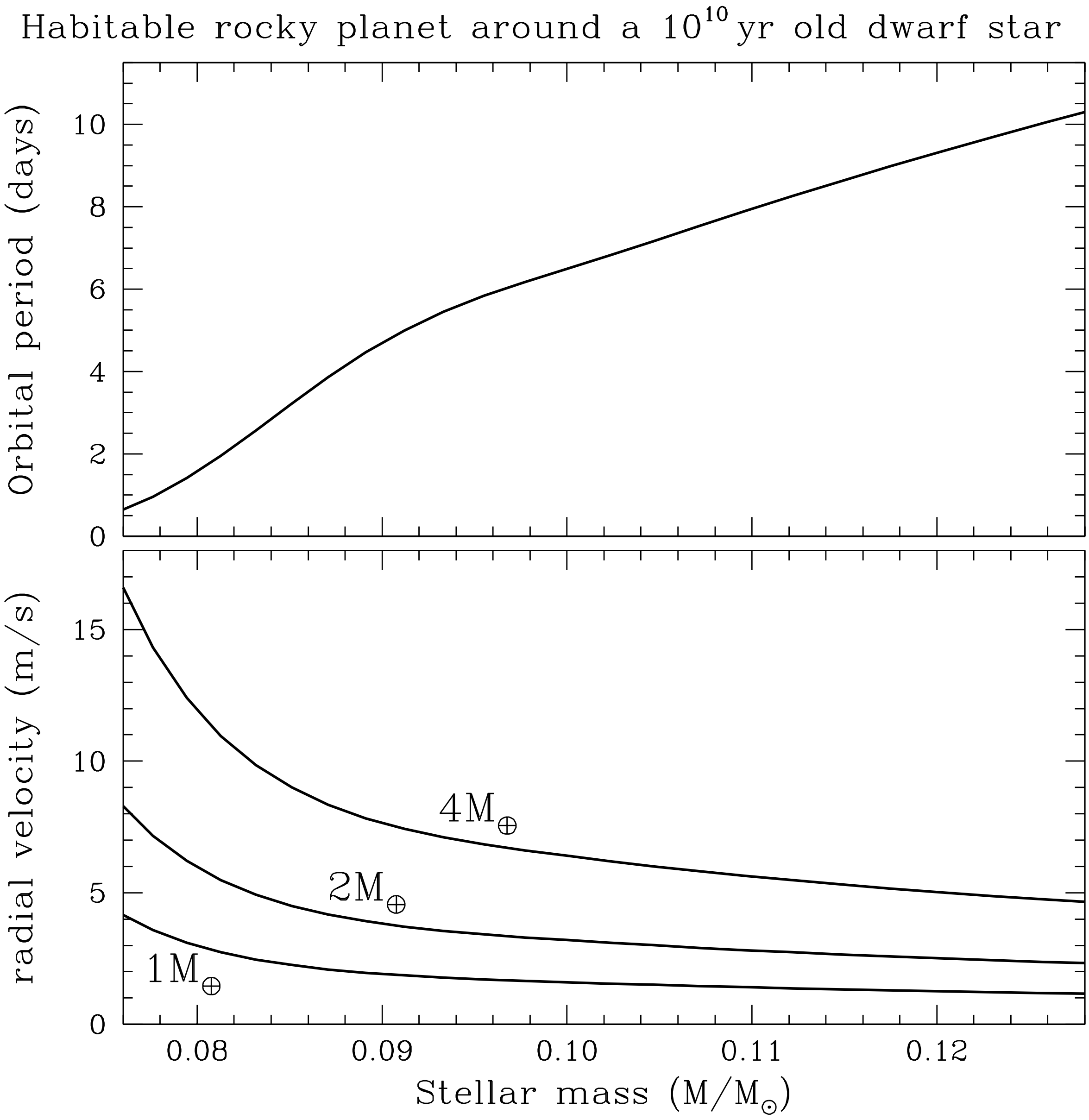

Figure 4. Upper panel: orbital period of a habitable planet around a 10 Gyr old main sequence star. The primary condition for habitability is that the stellar radiation flux on the planet surface is equal to that received by the Earth from the Sun.

Lower panel: stellar radial velocity variations induced by a habitable planet. The curves are for different planet masses (in Earth masses). The sharp decrease of orbital period and increase of radial velocity below 0.09 $M_{\odot}$ marks the transition from normal stars to brown dwarfs.