# Extrasolar Giant Planets: Masses and Luminosities from In-situ Formation Theories

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**Abstract.** Their expected luminosities make young giant planets favorable for the first direct detection of an extrasolar planet. The giant planet formation process is relatively slow with expected formation times ranging from comparable to the star formation timescale up to the nebula lifetime, depending on the formation theory. Therefore quantitative models of giant planet formation have to be considered when estimating young giant planet properties at pre-main sequence stellar ages. This is especially important for free-floating giant planet candidates where planetary nature is inferred from luminosities, without independent mass determinations. I will discuss observables of young- and proto-giant planets as they follow from the disk-instability and nucleated-instability hypothesis, respectively. The luminosity exceeds $10^{-4}\,\mathrm{L}_{\odot}$, even for a Saturn-mass protoplanet, during the brief, $3\,10^{4}$ year period around maximum accretion. Luminosity maxima of giant planets occur at ages of 1–10 Myr, depending on the details of the formation process. To infer planetary nature in a young population, the properties of young planets have to be compared to those of proto brown dwarfs, as they follow from the respective formation theories.

## 1 Luminosities for Young Giant Planets

Young[1] giant planets are much more luminous than present solar system giant planets, with $\sim 10^{-9}\,\mathrm{L}_{\odot}$ for Jupiter. Even a $20\,\mathrm{M}_{\oplus}$ protoplanet can radiate at $\sim 10^{-6}\,\mathrm{L}_{\odot}$, $= 1\,\mu\mathrm{L}_{\odot}$, the typical luminosity for young giant planets (cf. [10]). They are therefore much easier to detect, especially when they are at large orbital distances. Unfortunately solar system dimensions appear on the sub-arcsecond scale even in the closest young, star-formation regions. But ejection of young planets after close encounters with a massive body might still provide planetary objects separated far enough from their parent systems for convenient observation. In such a situation, that facilitates direct detection, the mass and therefore the planetary nature cannot be determined from the gravitational interaction with the primary of the parent system. It

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has to be estimated by direct study of the candidate object. This requires knowledge of the properties to be expected for such young giant planets, most prominently for detection purposes, their luminosity. If, in a known range of ages for the region under investigation, there is nothing else that can be as faint as a young planet at its brightest, the candidate object may be considered to be a planet.

Usually luminosities of young giant planets are taken from planetary evolution models, that were originally designed to understand solar system giant planet luminosities at ages comparable to the present solar system age. These models give relatively high luminosities ($> 10^{-6}\,\mathrm{L}_\odot$) for ages $< 10\,\mathrm{Myr}$, for a Jupiter mass (cf. [6]). They do not consider the formation process but assume an arbitrary hot inital state and argue that due to the short cooling times in the beginning, these initial conditions are rapidly forgotten and the results become independent of the initial assumptions. But the giant planet formation process itself occurs on the 10 Myr timescale. Therefore luminosities from such 'cooling' calculations cannot be used in the first $10^5$–$10^8\,\mathrm{yr}$ because they still show the memory of the artificial inital state [9].To obtain physically plausible luminosities for young giant planets they have to be calculated from formation theories. I present results obtained in the nucleated instability hypothesis, where a core grows first, and the disk instability hypothesis, that involves giant gaseous protoplanets. I compare those luminosities to the luminosities for stars and brown dwarfs, as they follow from the respective formation theories for the first Myrs.

## 2 Luminosities and Formation Theories

The relatively high luminosities of young giant planets occur for two main reasons: (1) the planets are still hot because the cooling just started and (2) the accretion process itself adds to the luminosity, e.g., when gas flowing onto the protoplanet is stopped at its 'surface'. The two reasons are interdependent because energy radiated away during the accretion process will not be stored into the interior of the planet for later release during the cooling phase. Early high luminosity phases due to the accretion process leave less energy for later, high luminosity cooling phases. Because of the unimportance of nuclear energy generation, the luminosity radiated over all time is limited to the binding energy of the cooled planet. Hence the accretion history is important for the early cooling history and I will give examples from two formation theories.

All calculations that I present use a new, time-dependent convection model [13] that is derived from the model of Kuhfuß (1987), [7]. It closely approximates standard mixing length theory in a local, static limit and has been successfully tested in calculations of the Sun and RR-Lyrae pulsations [13]. To determine the protoplanetary luminosities, the equations of radiation hydrodynamics with spherical symmetry, supplemented by the convection model, are solved with a 'protoplanetary' version of the VIP-code [4], where convection is added as outlined in [12]. The convection model is used with the standard parameters given in [13]. Equations of state (as in [10]) and opacities are for solar composition. Opacities include the contribution of dust particels with 'interstellar' properties and Alexander and Ferguson (1994) values, [1], in the molecular range (compilation by [5]). Deuterium burning and convective mixing are included. For the formulation of equations and boundary conditions see [10].

### 2.1 The Nucleated Instability Hypothesis

The Nucleated Instability Hypothesis is based on the 'planetesimal hypothesis' that assumes that planets grow within circumstellar disks via accretion of km-sized solid bodies, the so-called planetesimals. Sufficiently massive planetesimals embedded in a gravitationally stable preplanetary nebula can capture large amounts of gas and become the cores of giant planets. In this hypothesis one formation mechanism accounts for small solar system objects, terrestrial planets and giant planets. It is the only formation model for Uranus and Neptune type planets (see [14] for a review). In Figs. 1 and 2

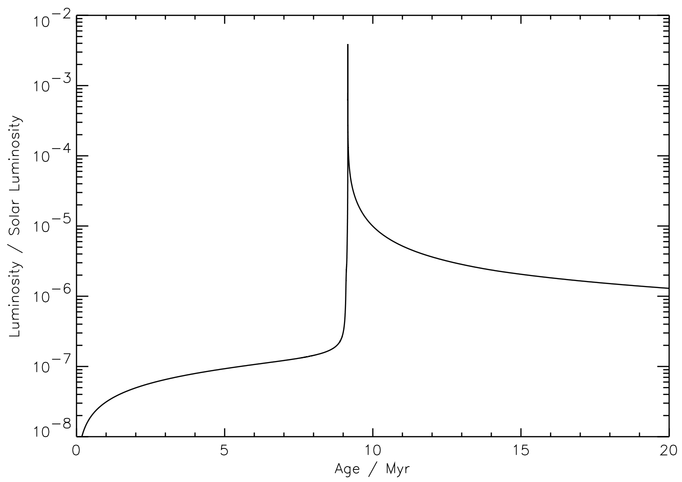


**Fig. 1.** Luminosity of a young giant planet that grows at an orbital distance of 5.2 AU from a solar mass star, according to the nucleated instability hypothesis. The final mass is $106\,\mathrm{M}_\oplus$ with $9.2\,\mathrm{M}_\oplus$ in the core, i.e. similar to Saturn. The peak luminosity is reached at the moment of maximum accretion, $\dot{M} \sim 0.14\,\mathrm{M}_\oplus/\mathrm{yr}$. That moment is reached after the core has grown to $9.2\,\mathrm{M}_\oplus$ with a constant accretion rate of $\dot{M}_{\mathrm{core}} = 10^{-6}\,\mathrm{M}_\oplus/\mathrm{yr}$. The width of the luminosity peak is 30000 yr at $10^{-4}\,\mathrm{L}_\odot$, cf. Fig. 2

results from a nucleated instability model for a proto giant planet growing at an orbital distance of 5.2 AU in a minimum mass nebula [8] and constant core accretion rate of $10^{-6}\mathrm{M}_\oplus/\mathrm{yr}$ are shown (for a discussion see [14]). When the envelope mass reaches $97\,\mathrm{M}_\oplus$ the protoplanet is shut off from the nebula and the following evolution is calculated at constant mass.

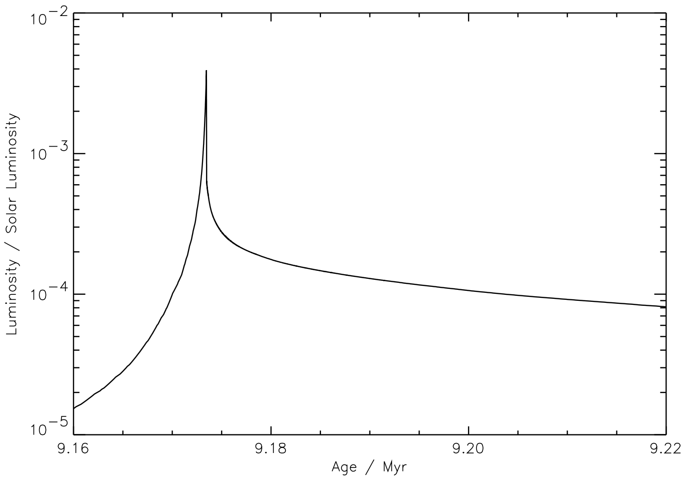


**Fig. 2.** Luminosity of a protogiant planet in the vicinity of maximum accretion. Detail of Fig. 1. The young giant planet is brighter than $10^{-4}\,\mathrm{L}_\odot$ for about 30000 yr

### 2.2 Disk Instability and Giant Gaseous Protoplanets

Protoplanetary disks are considered to be gravitationally stable and self-stabilizing (see [14], for a discussion in the context of giant planet formation). But it has been claimed that a disk instability might be triggered by an external perturbation and giant planets might form via a tenuous intermediate stage as giant gaseous protoplanet (GGPP), [2]. The luminosity of a GGPP in the first Myr is estimated here by a radiation hydrodynamical calculation with the same assumptions as above, for the nucleated instability hypothesis, but without a core. The initial condition was a gravitationally unstable nebula condensation of a Jupiter-mass, $\mathrm{M_J}$ and a temperature of 10 K. Initially the GGPP had similar properties as the banana-shaped density enhancements found in [2] (mean density $8 \times 10^{-10}\,\mathrm{g\,cm^{-3}}$, central density $3.3 \times 10^{-8}\,\mathrm{g\,cm^{-3}}$). The results for this case and for $5\,\mathrm{M_J} \sim 0.005\,\mathrm{M}_\odot$ are displayed as the lowest two full lines in Fig. 3. Because a Jupiter mass is optically thick under nebula conditions, the $1\,\mathrm{M_J}$ GGPP does not collapse immediately, but cools for $\sim 1\,\mathrm{Myr}$ at a luminosity around a $\mu\,\mathrm{L}_\odot$. The luminosity rise at the end of the depicted evolution indicates the onset of the final collapse to planetary densities.

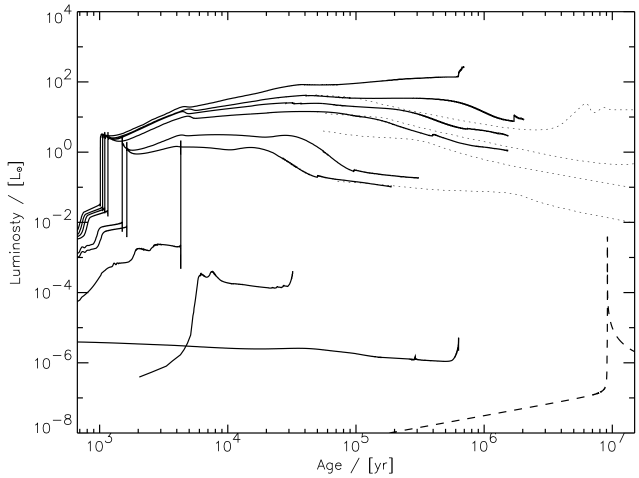


**Fig. 3.** Comparison of young stars, young brown dwarfs and young planets in the first 10 Myr as calculated from formation theories. The hydrodynamic evolution of gravitationally unstable cloud fragments of $10, 2, 1, 0.5, 0.1\,\mathrm{M}_\odot$ (protostars), $0.05, 0.01\,\mathrm{M}_\odot$ ( proto brown dwarfs), and $0.005, 0.001\,\mathrm{M}_\odot$ (giant gaseous protoplanets) are depicted as full lines, from top to bottom, respectively, together with the Saturn-mass proto giant planet (dashed) that has been calculated according to the nucleated instability hypothesis as discussed in Sect. 2.1 (cf. Figs. 1,2). Age is measured from the moment when the Rosseland-mean optical depth exceeds unity. Note the initial rises in luminosity, that are not present in evolutionary calculations that do not consider the formation process. For the planets, the formation of the core and the cooling in the case of the lowest mass GGPP, delay the luminosity peaks on the Myr timescale. Clearly the formation process has to be considered when discussing luminosities in a young population. The luminosity evolution for $2, 1, 0.5, 0.1\,\mathrm{M}_\odot$ (dotted lines from top to bottom) as obtained from standard quasi-hydrostatic stellar pre-main sequence calculations ([3], 'MLT+Alexander') are plotted for comparison.

## 3 Zero Age for Planets, Brown Dwarfs and Stars

To compare the luminosities of objects of various masses at a given age a general definition of zero age is necessary. Because the thermally controlled Kelvin-Helmholtz contraction is the dominating evolutionary process in young gas spheres, whether they are giant planets, brown dwarfs or stars, I propose, to use the instant of time, when the interior of the gas-spheres is thermally enclosed for the first time, as age zero. The enclosure means that photons emitted as a consequence of an evolutionary change in the gas sphere cannot escape from the entire object directly and as soon as it changes — as is the case in the earliest isothermal cloud phases — but that they are radiated from a photosphere. Energy transfer to the photospheric bottleneck then delays the cooling and determines how the thermal reservoir in the interior is emptied. The cooling history can than be used to define an age since the heat reservoir was formed. As a practical definition for age zero I propose to use the instant of time when the Rosseland mean optical depth of a gaseous object exceeds unity. For a protostar this instant of time is practically at the end of the isothermal phase of the collapse. With that definition the luminosities of the protoplanets can be compared to stars and brown dwarfs of similar age.

## 4 A Comparison of the Luminosities of Young Planets, Brown Dwarfs and Stars

To finally address the question whether a young giant planet can be distinguished by its luminosity from a young brown dwarf or a young star of a similar age I present radiation hydrodynamical calculations of the formation of stars and brown dwarfs for the identical physical assumptions that were used to discuss planet formation above. The resulting luminosities in the first 10 Myr are compared to those of the giant planets in Fig. 3. I will discuss one important issue that follows from Fig. 3: the time delay between the 'initial' luminosity rise of stars and planets. Whereas protostars of all masses that are shown dramatically increase their luminosity within 2000 yr of cloud condensation and becoming optically thick, the luminosity increase for giant planets (with masses $< 0.05\,\mathrm{M}_\odot$) is much slower. They need up to 10 Myr to reach their maximum accretion phase and, as a consequence, their maximum luminosity which is the starting point for their final contraction and cooling phase. This delay has an interesting consequence: A Saturn mass proto giant planet with the main accretion nucleated after 9 Myr almost outshines a $0.1\,\mathrm{M}_\odot$ star of the same age, for a few 1000 yr.

## 5 Conclusion

The luminosity for a Saturn-mass protoplanet exceeds $10^{-4}\,\mathrm{L}_\odot$, during the brief, $3\,10^4$ year period around maximum accretion. Luminosity maxima of giant planets occur at ages of 1–10 Myr, depending on the details of the formation process. To infer planetary nature in a young population, the properties of young planets have to be compared to those of proto brown dwarfs, as follows from the respective formation theories.

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