Recent progress in astronomical nomenclature in the relativistic framework

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Barycentric Celestial Reference System

The BCRS:

- adopted by the International Astronomical Union (2000)
- suitable to model high-accuracy astronomical observations

$$g_{00} = -1 + \frac{2}{c^2} w(t, \boldsymbol{x}) - \frac{2}{c^4} w^2(t, \boldsymbol{x}) \, ,$$

$$g_{0i} = -\frac{4}{c^3} w^i(t, \boldsymbol{x}) \, ,$$

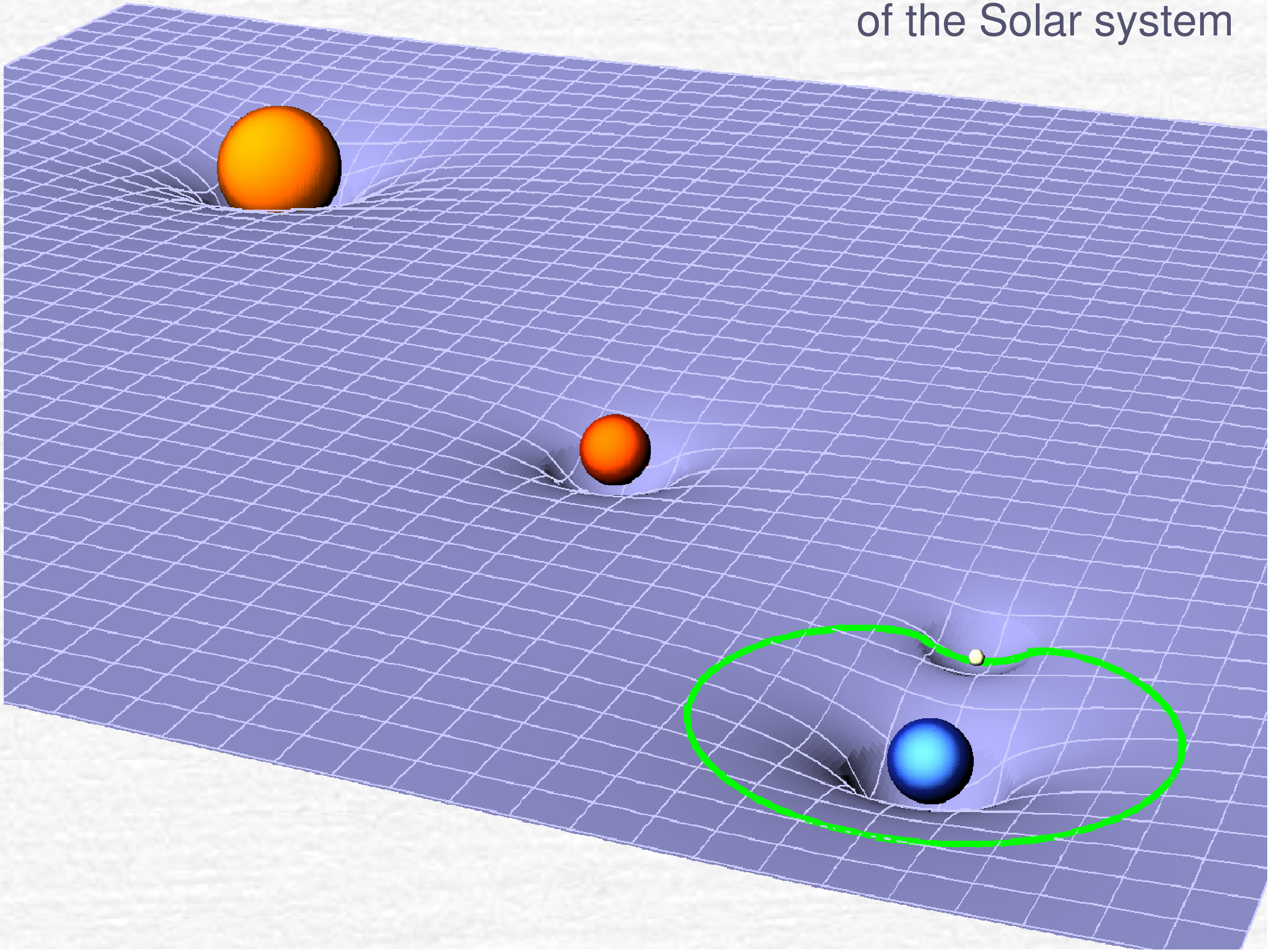
$$g_{ij} = \delta_{ij} \left(1 + \frac{2}{c^2} w(t, \boldsymbol{x}) \right) .$$

w, w^i : relativistic gravitational potentials

Barycentric Celestial Reference System

The BCRS is a particular reference system in the curved space-time of the Solar system

- One can use any
- but one should be fixed



BCRS is a 'dynamical concept'

- BCRS defines the form of the equations of motion (bodies and light-rays)
  and thus fixes the coordinates up to

--- linear transformations of the time variable

--- a constant rotation of spatial coordinates

- Adopting the BCRS in the post-Newtonian framework
  is similar to adopting the Newtonian equations of motion
  without Coriolis and Centrifugal terms in the Newtonian framework

Fixing the degrees of freedom in the 2000 definition of the BCRS

- Similar to the degrees of freedom of a reference system where the Newtonian equations of motion without Coriolis and Centrifugal forces are valid:

(0. constant shift in space: fixed by the word “Barycentric”)

1. constant shift in time: fixed by the definition TCB given in 1991
2. Orientation of spatial coordinates: not fixed up to now

   - irrelevant for physical laws (e.g., equations of motion): space is isotropic
   - one of the major concerns of astrometry
   - fixed now by the ICRS orientation

Geocentric Celestial Reference System

The GCRS is adopted by the International Astronomical Union (2000) to model physical processes in the vicinity of the Earth:

A: The gravitational field of external bodies is represented only in the form of a relativistic tidal potential.

B: The internal gravitational field of the Earth coincides with the gravitational field of a corresponding isolated Earth.

$$G_{00} = -1 + \frac{2}{c^2} W(T, \boldsymbol{X}) - \frac{2}{c^4} W^2(T, \boldsymbol{X}) \,,$$

$$G_{0a} = -\frac{4}{c^3} W^a(T, \boldsymbol{X}) \,,$$

$$G_{ab} = \delta_{ab} \left(1 + \frac{2}{c^2} W(T, \boldsymbol{X}) \right).$$

W, W^a : internal + inertial + tidal (external) potentials

Degrees of freedom in the GCRS definition

- GCRS is again a dynamical concept fixing the equations of motion
- Again one has in principle the same degrees of freedom

HOWEVER

the IAU 2000 framework explicitly gives the full form of the coordinate transformations between BCRS and GCRS!

- Once the BCRS coordinates are fully fixed, the GCRS coordinates become also fully fixed through the given coordinate transformations:

If BCRS is spatially oriented according to the ICRS →

the spatial GCRS (kinematically non-rotating) coordinates will get an "ICRS-induced" orientation

The orientations of BCRS and GCRS are NOT "the same"!

- It is confusing and even dangerous in many situations to think that the GCRS has "the same" spatial orientation as the BCRS (or ICRS)

- The transformations between BCRS and GCRS are 4-dimensional time-dependent Lorentz-like transformations

- For example: a BCRS vector $(t,1,0,0)$ is NOT transformed into the GCRS vector $(T,1,0,0)$

- The difference in spatial coordinates cannot be described by shift of origin plus rotation

- It amounts to a few milliarcseconds (of order $(v/c)^2$)

- It is taken into account by *relativistic models (VLBI, astrometry ...)*

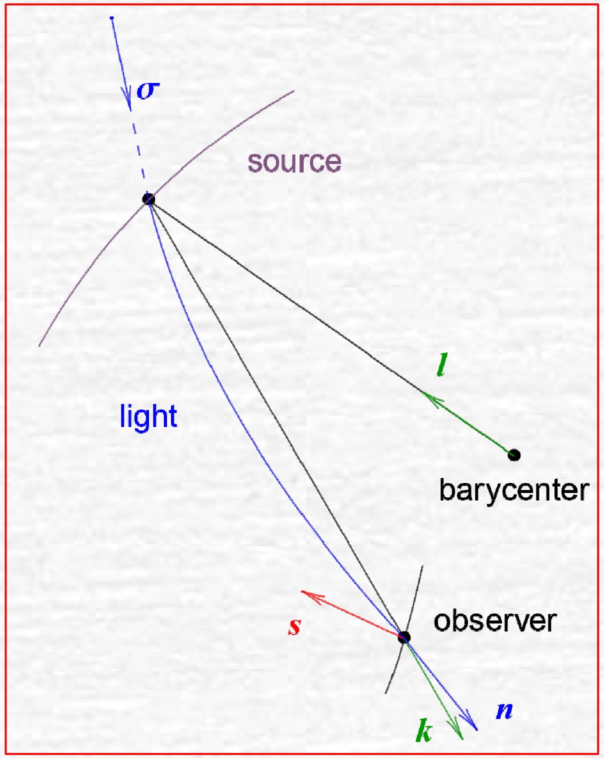
Relativistic Aberration

- Lorentz transformation with the scaled velocity of the observer:

$$\boldsymbol{s} = \left(-\boldsymbol{n} + \left\{ \frac{\gamma}{c} - (\gamma - 1)\,\frac{\boldsymbol{v}\cdot\boldsymbol{n}}{v^2} \right\} \boldsymbol{v} \right) \frac{1}{\gamma\,(1 - \boldsymbol{v}\cdot\boldsymbol{n}/c)},$$

$$\gamma = \left(1 - v^2/c^2\right)^{-1/2},$$

$$\boldsymbol{v} = \dot{\boldsymbol{x}}_o \left(1 + \frac{2}{c^2}\, w(t, \boldsymbol{x}_o) \right)$$



- For an observer on the Earth or on a typical satellite:

  - Newtonian aberration ~20″
  - relativistic aberration ~ 4 mas
  - second-order relativistic aberration ~ 1 μas

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Merging TDB with T_{eph}

- Original definition of TDB (1976): TDB-TT should contain only periodic terms
- Danger: defined in such a way TDB is NOT a linear function of TCB
- Why is it a danger?

  The relativistic Einstein-Infeld-Hoffman (EIH) equations of motion
  that have been used to produce planetary ephemerides since about 1970
  are valid ONLY with TCB or a linear function thereof!

- T_{eph} was introduced by Myles Standish (1998) as a reaction to this concern

  T_{eph} is a linear function of TCB by definition;
  the rate depends on the particular ephemeris and is chosen
  so that the secular part of T_{eph} - TT is as close to zero as possible

- Claim: TDB as defined 1976 has never been in use;
  In all cases where TDB was claimed to be used, it was
  T_{eph} that was used instead

Merging TDB with T_{eph}

- A natural way to proceed:

  forget the flawed TDB definition and re-define it to coincide with $T_{eph:}$

- Glossary of the IAU Working Group on Nomenclature:

Barycentric Dynamical Time (TDB): a time scale originally intended to serve as an independent time argument of barycentric ephemerides and equations of motion. TDB was defined by the IAU 1976 resolutions to differ from Terrestrial Time (TT) only by periodic terms. Later it became clear that this condition cannot be satisfied rigorously. The IAU 1991 resolutions defined TDB as a linear function of TCB without fixing the rate ratio. Each ephemeris defines its own version of TDB: the linear drift between TDB and TCB is chosen so that the rates of TDB and TT are as close as possible for the time span covered by the particular ephemeris. TDB is sometimes designated by T_{eph}.

Barycentric Ephemeris Time (T_{eph}): **see** Barycentric Dynamical Time (TDB).

Day, Julian year, Julian century, Julian date

- Day, Julian year and Julian century are just multiples of the SI second:

  1 d = 86400 s
  1 Julian year = 365.25 d
  1 Julian century = 36525 d

- These “units” can be used with ANY time scale:

  TT, TCB, TCB, TDB, proper time of any observer

- Julian date also can be used with ANY time scale:

1. On 1977 January 1, $00^h\ 00^m\ 00^s$ TAI at the geocenter, the readings of TT, TCG and TCB are 1977 January 1, $00^h\ 00^m\ 32^s.184$ (JD 244 3144.5003725).

2. The equivalent TDB reading depends upon the adopted ephemeris: the same reading for TDB(DE405) is JD 244 3144.5003725 – 65.564518 μs.

“TDB units” vs. “TDB values” in SI units

- there still seems to be some kind of confusion with the wordings “TDB units” vs. TDB-values in “SI units” throughout the documents…

Problems discussed in detail in:

S.Klioner, Relativistic astronomical time scales, relativistic scaling of astronomical constants and the system of astronomical units

to be published (A&A)

END